Lucid Synchrone, version 3

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Lucid Synchrone

Release, version 3.0

Tutorial and Reference Manual

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Contents

Foreword

This document describes Lucid Synchrone, a dedicated to the implementation of reactive systems. Lucid Synchrone [1] is an ML-extension of the synchronous data-flow language Lustre [4]. The main features of the language are the following:

- The language has a data-flow flavor *à la* Lustre and the syntax is largely reminiscent to the one of Objective Caml [7]. It manages infinite sequences or streams as primitive values. These streams are used for representing input and output signals of a reactive system.
- The language provides some classical features of ML languages such as higher-order (a function can be parameterized by a function or return a function) or type inference.
- The language is build on the notion of *clocks* as a way to specify different execution rates in a program. In Lucid Synchrone, clocks are types and are computed automatically.
- Two program analysis are also provided. A causality analysis rejects programs which cannot be statically scheduled and an initialization analysis rejects programs whose behavior depends on uninitialized delays.
- The language allows for the definition of data-types: product types, record types and sum types. Structured values can be accessed through a pattern matching construction.
- Programs are compiled into Objective Caml. When required (through a compilation flag), the compiler ensures that the resulting program is "real-time", i.e., it uses bounded memory and has a bounded response time for all possible program inputs.
- A module system is provided for importing values from the host language Objective Caml or from other synchronous modules.

Version `3` is a major revision and offers new features with respect to versions `1.0` and `2.0`.

- The language allows to combine data-flow equations with complex state machines with various forms of transitions).
- Activation conditions are done through a pattern matching mechanism.
- Besides the regular delay primitive `pre`, a new delay primitive called `last` has been added in order to make the communication between shared variables in control structures (activation conditions or automata) easier.

[1] The name is built from Lucid [1] and from the French word "synchrone" (for "synchronous").

- The language provides a way to define static values (i.e., infinite constant sequences). These static values may be arbitrarily complex but the compiler guaranty that they can be computed once for all, at instantiation time, before the first reaction starts.
- It is possible to define valued *signals*. Signals are stream values paired with a presence information (called *enable* in circuit terminology). The value of signal can be accessed through a pattern matching construct.
- The language supports streams of functions as a way to describe reconfigurable systems.
- *Sequential* functions (as opposed to *combinatorial* function to keep circuit terminology) must now be explicitly declared with the keyword `node`. Otherwise, they are considered to be *combinatorial*.
- Internally, the compiler has been completely rewritten. We abandoned the compilation method introduced in version `2.0` and came back to the (co-iteration based) compilation method introduced in version `1.0`.

Availability

The current implementation is written in Objective Caml. The use of the language needs the installation of Objective Caml.

Lucid Synchrone, version 3.0: `http://www.lri.fr/~pouzet/lucid-synchrone`
Objective Caml, version 3.09: `http://www.ocaml.org`

The language is experimental and evolves continuously. Please send comments or bug to `Marc.Pouzet@lri.fr`.

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Part I

Lucid Synchrone

Chapter 1

An introduction to Lucid Synchrone

This section is a tutorial introduction to Lucid Synchrone. A good familiarity with general programming languages is assumed. Some familiarity with (strict or lazy) ML languages and with existing synchronous data-flow languages would be helpful since the language incorporates features from both families. Some references are given at the end of this document.

For this tutorial, we suppose that programs are written in a file `tutorial.ls`.

1.1 The core language

1.1.1 Point-wise Operations

The language is a functional language, with a syntax close to Objective Caml. As in Lustre, every ground type or any scalar value imported from the host language, Objective Caml, is implicitly lifted to streams. Thus:

- `int` stands for the type of streams of integers,
- `1` stands for the constant stream of values 1,
- `+` adds point-wisely its two input streams. It can be seen as an adder circuit, in the same way, `&` can be seen as an "and" gate.

Program executions can be represented as *chronograms*, showing the sequence of values taken by streams during the execution. The example below shows five streams, one per line. The first line shows the value of a stream `c`, which has the value t (*true*) at the first instant, f (*false*) at the second one, and t at the third. The notation ... indicates that the stream has more values (it is infinite), not represented here. Similarly, the following lines define `x` and `y`. The fourth line define a stream obtained by adding `x` and `y`, addition is done point-wisely.

`c`	t	f	t	...
`x`	x_0	x_1	x_2	...
`y`	y_0	y_1	y_2	...
`x+y`	$x_0 + y_0$	$x_1 + y_1$	$x_2 + y_2$	...
`if c then x else y`	x_0	y_1	x_2	...

1.1.2 Delays

`fby` is a delay operator. The expression `x fby y`, which can be read as "`x` *followed by* `y`" takes the first value of `x` at the first instant, then takes the previous value of `y`. In other words, it delays `y` by one instant, and is initialized by `x`.

x	x_0	x_1	x_2	...
y	y_0	y_1	y_2	...
x fby y	x_0	y_0	y_1	...

It is often needed to separate the delay from the initialization. This is done using the delay operator `pre`, and the initialization operator `->`. `pre x` delays its argument `x`, and has an unspecified value (denoted here by *nil*) at the first instant. `x -> y` takes the first value of x at the first instant, then the current value of y. The expression `x -> (pre y)` is equivalent to `x fby y`.

x	x_0	x_1	x_2	...
y	y_0	y_1	y_2	...
pre x	*nil*	x_0	x_1	...
x -> y	x_0	y_1	y_2	...

The *initialization check* made by the compiler checks that the behavior of a program never depends on the value *nil*. See section 1.1.10 for details.
Warning: A common error with the initialization operator is to use it for defining the first two values of a stream. This does not work, since `x -> y -> z` = `x -> z`. One should instead write `x fby y fby z` or, `x -> pre (y -> pre z)`.

1.1.3 Global declarations

A program is made of a sequence of declarations of global values. `let` defines non recursive global values whereas `let rec` define recursive global values. These global values may be (infinite) constant streams or functions. For example:

```
let dt = 0.001
let g = 9.81
```

These declarations define two infinite constant streams `dt` and `g`. The type and clock of each expression are infered, the compiler can display them by using the option `-i`:

```
$ lucyc -i tutorial.ls
val dt :  float
val dt :: static
val g :  float
val g :: static
```

For each declaration, we get the inferred type and clock. Clocks will be explained further in a later part.

Only constant values can be defined globally, thus rejecting the following program:

```
let init = true -> false
```

Trying to compile this program, we get the following answer:

```
$ lucyc tutorial.ls
File "tutorial.ls", line 1, characters 11-24:
>let init = true -> false
>           ^^^^^^^^^^^^^
This expression should be combinatorial.
```

The right part of a global `let` declaration cannot contain any delay operations. Definitions containing delays are sequential and introduced by the notation `node` (see 1.1.5).

1.1.4 Combinatorial Functions

Stream functions are separated into *combinatorial* and *sequential* functions. A function is combinatorial when its output at instant n depends only on its input at the same instant n.

The definition of combinatorial function uses the `let` notation seen previously. Consider, for example, the function computing the average of its two inputs. We directly give its type and clock signatures as computed by the compiler.

```
let average (x,y) = (x + y) / 2

val average :  int * int -> int
val average :: 'a * 'a -> 'a
```

This function get the type signature `int * int -> int` stating that it takes two integer streams and returns an integer stream. Its clock signature states that it is a *length preserving function*, that is, it returns a value for every input.

Function definition can contain local declarations, introduced using either the `where`, or the `let` notation (see 1.1.7). For example the average function can be written:

```
let average (x,y) = o where
  o = (x + y) / 2

let average (x,y) =
  let o = (x + y) / 2 in
  o
```

As another example of combinatorial program, we end with the classical description of a one-bit adder. A full adder takes three bits (`a`, `b` and a carry bit `c`) and it returns the result `c` and the new carry `co`.

```
let xor (a, b) = (a & not(b)) or (not a & b)

let full_add(a, b, c) = (s, co) where
       s = xor (xor (a, b), c)
   and co = (a & b) or (b & c) or (a & c)

val xor :  bool * bool -> bool
val xor :: 'a * 'a -> 'a
val full_add :  bool * bool * bool -> bool * bool
val full_add :: 'a * 'a * 'a -> 'a * 'a
```

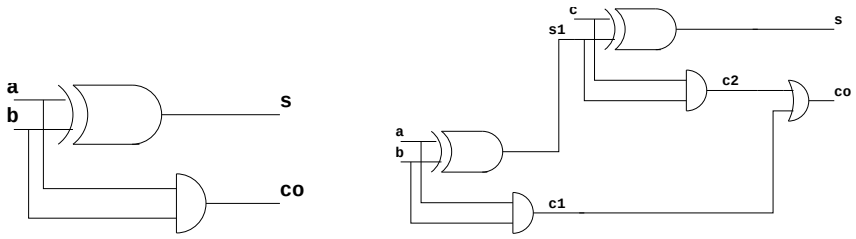


Figure 1.1: A half-adder and a full-adder

A full adder can be described more efficiently as a composition of two half adders. The graphical description is given in figure 1.1 and it corresponds to the following code:

```
let half_add(a,b) = (s, co)
   where
       s = xor (a, b)
   and co = a & b

val half_add :  bool * bool -> bool * bool
val half_add :: 'a * 'a -> 'a * 'a

let full_add(a,b,c) = (s, co)
  where
  rec (s1, c1) = half_add(a,b)
  and (s, c2) = half_add(c, s1)
  and co = c1 or c2

val full_add :  bool * bool * bool -> bool * bool
val full_add :: 'a * 'a * 'a -> 'a * 'a * 'a
```

1.1.5 Sequential Functions

Sequential functions (or state functions) are such that their output at instant n may depend on the history of their inputs, that is, input values of instants k ($k \leq n$).

To generalise, an expression is called sequential if it may produce a time evolving value when its free variables are kept constant. Otherwise, we call it combinatorial. A sufficient condition to be a combinatorial expression is not to contain any delay, initialization operator, nor state machine. This is verified by type checking.

Sequential functions are introduced by the keyword `node`. They receive a different type signature than the one given to combinatorial functions. The type signature `int => int` states that `from` is a stream function from an integer stream to an integer stream and that its output may depend on the history of its input.

The following function computes the sequence of integers starting at some initial value given by parameter `m`:

```
let node from m = nat where
  rec nat = m -> pre nat + 1

val from :  int => int
val from :: 'a -> 'a
```

Applying this function to the constant stream `0` yields the following execution:

`m`	0	0	0	0	0	0	...
`1`	1	1	1	1	1	1	...
`pre nat`	*nil*	0	1	2	3	4	...
`pre nat + 1`	*nil*	1	2	3	4	5	...
`m -> pre nat + 1`	0	1	2	3	4	5	...
`from m`	0	1	2	3	4	5	...

Combinatorial functions are checked to be combinatorial at compile time, thus forgetting the keyword `node` leads to an error:

```
let from n = nat where
  rec nat = n -> pre nat + 1
```

and we get:

```
$ lucyc tutorial.ls
File "tutorial.ls", line 16, characters 12-28:
>  rec nat = n -> pre nat + 1
>            ^^^^^^^^^^^^^^^^
This expression should be combinatorial.
```

We can define an edge detector in the following way:

```
let node edge c = c & not (false fby c)
```

`c`	*f*	*f*	*t*	*t*	*f*	*t*	...
`false`	*f*	*f*	*f*	*f*	*f*	*f*	...
`false fby c`	*f*	*f*	*f*	*t*	*t*	*f*	...
`not (false fby c)`	*t*	*t*	*t*	*f*	*f*	*t*	...
`edge c`	*f*	*f*	*t*	*f*	*f*	*t*	...

`edge` is a global function from boolean streams to boolean streams.

An integrator is defined by:

```
let dt = 0.01

let node integr x0 dx = x where
  rec x = x0 -> pre x +. dx *. dt

val integr :  float -> float => float
val integr :: 'a -> 'a -> 'a
```

`integr` is a global function returning a stream `x` defined recursively. The operators `+.`, `*.` stand for the addition and multiplication over floating point numbers. Sequential functions may be composed as any other functions. For example:

```
let node double_integr x0 dx0 d2x = x where
  rec x = integr x0 dx
  and dx = integr dx0 d2x
```

It is possible to build functions from other functions by applying the later only partially. For example:

```
let integr0 = integr 0.0
```

Which is equivalent to:

```
  let node integr0 dx = integr 0.0 dx
```

1.1.6 Anonymous Functions

Functions can be defined in an anonymous way and can be used as values. Anonymous combinatorial functions are introduced using a single arrow (`->`), anonymous sequential ones using a double arrow (`=>`). For example, the expression `fun x y -> x + y` is the sum function and has type `int -> int -> int`). The expression `fun x y => x fby x fby y` defines a double delay and has the type `'a -> 'a => 'a`.

The functions `average` and `from` can be defined as:

```
let average = fun (x,y) -> (x + y) / 2
let from = fun n => nat where rec nat = n -> pre nat + 1
```

1.1.7 Local definitions and Mutually Recursive Definition

Variables may be defined locally with a `let/in` or `let rec/in` and there is no special restriction on the expressions appearing on the right of a definition. The following program, computes the Euclidean distance between two points:

```
let distance (x0,y0) (x1,y1) =
  let d0 = x1 -. x0 in
  let d1 = y1 -. x1 in
  sqrt (d0 *. d0 +. d1 *. d1)
```

Notice that because `d0` and `d1` denote infinite sequences, the computations of `x1 -. x0` and `y1 -. x1` are (virtually) executed in parallel. Nonetheless, when writing sequences of definitions `let/in` such as above, the sequential order is preserved for each reaction of the system, that is, the current value of `d0` is always computed before the current value of `d1`. This sequential order may be of importance if side-effects are present.

Streams may be defined as a set of mutually recursive equations. The function which computes the minimum and maximum of some input sequence `x` can be written in (at least) the three equivalent ways:

```
let node min_max x = (min, max) where
  rec min = x -> if x < pre min then x else pre min
  and max = x -> if x > pre max then x else pre max

let node min_max x =
  let rec min = x -> if x < pre min then x else pre min
  and max = x -> if x > pre max then x else pre max in
  (min, max)

let node min_max x = (min, max) where
  rec (min, max) = (x, x) -> if x < pre min then (x, pre max)
                             else if x > pre max then (pre min, x)
                             else (pre min, pre max)
```

The classical sinus and co-sinus functions can be defined like the following:

```
let node sin_cos theta = (sin, cos) where
  rec sin = theta *. integr 0.0 cos
  and cos = theta *. integr 1.0 (0.0 -> -. (pre sin))
```

We end with the programming of a mouse controller, a very classical example. Its specification is the following:

> Return the event `double` when two `click` has been received in less than four `top`.
> Emits `simple` if only one click has been received.

And here is a possible implementation:

```
(* counts the number of events from the last reset res *)
let node counter (res,event) = count where
  rec count = if res then 0 else x
  and x = 0 -> if event then pre count + 1 else pre count

let node mouse (click,top) = (single,double) where
  rec counting = click -> if click & not (pre counting) then true
                          else if res & pre counting then false
                          else pre counting
  and count = counter(res,top & counting)
  and single = ((0 fby count) = 3) & top & not click
  and double = (false fby counting) & click
  and res = single or double
```

1.1.8 Shared Memory and Initialization

The language provides an alternative way to the use of the delay `pre` in order to refer to the previous value of a stream. If `o` is a stream variable defined by some equation, `last o` refers to the last value of `o`. For example:

```
let node counter i = o where
  rec last o = i
  and o = last o + 1
```

The equation `last o = i` defines the *memory* `last o`. This memory is initialized with the first value of `i` and then, contains the previous value of `o`. The above program is thus equivalent to the following one [1]:

```
let node counter i = o where
  rec last_o = i -> pre o
  and o = last_o + 1
```

The memory `last o` will play an important role when combined with control structures. This will be detailed later.

From a syntactical point of view, `last` is *not* an operator: `last o` denotes a shared memory and the argument of `last` is necessarily a name. Thus the following program:

```
let node f () = o where
  rec o = 0 -> last (o + 1)
```

is rejected and we get:

```
File "tutorial.ls", line 55, characters 21-22:
>  rec o = 0 -> last (o + 1)
>                     ^
Syntax error.
```

1.1.9 Causality check

Recursively defined values must not contain any *instantaneous* or *causality* loops in order to be able to compute values in a sequential way. For example, if we type:

```
let node from m = nat where
  rec nat = m -> nat + 1
```

the compiler emits the message:

```
File "tutorial.ls", line 35, characters 12-24:
>  rec nat = m -> nat + 1
>            ^^^^^^^^^^^^
This expression may depend instantaneously of itself.
```

This program cannot be computed as `nat` depends on `nat` instantaneously.

The compiler statically reject program which cannot be scheduled sequentially, that is streams whose value at instant n may depend on some value at instant n. In practice, it imposes that any loop crosses a delay `pre` or `fby`.

In the current version of the compiler, the causality analysis reject recursions which are not explicitely done through a delay. The following program (which is semantically correct) is rejected:

```
let node f x = 0 -> pre (x + 1)

let node wrong () =
  let rec o = f o in o
```

[1] The construction `last` is eliminated during the compilation process by a similar transformation.

1.1.10 Initialization check

The compiler checks that every delay operator is initialized. For example:

```
let node from m = nat where
  rec nat = pre nat + 1

File "tutorial.ls", line 35, characters 12-23:
>  rec nat = pre nat + 1
>            ^^^^^^^^^^^
This expression may not be initialised.
```

The analysis is a *one-bit* analysis where expressions are considered to be either always defined or always defined except at the very first instant. It is precisely defined in [3]. In practice, it rejects expressions like `pre (pre e)`, that is, un-initialized expressions cannot be used as an argument of a delay and must be first initialized using `->`.

1.2 Multi-clock systems

Up to now, we have only considered length preserving functions, that is, functions returning n items of their output when receiving n items of their input. We consider now a more general case allowing to sample stream and to compose them. This is achieved through the use of *clocks*.

1.2.1 Sampling: the operator `when`

`when` is a sampler that allows fast processes to communicate with slower ones by extracting sub-streams from streams according to a condition, *i.e.* a boolean stream.

`true`	t	t	t	t	...
`c`	f	t	f	t	...
`x`	x_0	x_1	x_2	x_3	...
`x when c`		x_1		x_3	...
`true on c`	f	t	f	t	...

The sampling operators introduce the notion of *clock* type. These clock types give some information about the time behavior of stream programs.

The clock of a stream s is a boolean sequence giving the instants where s is defined. Among these clocks, the base clock stands for the constant stream `true`: a stream on the base clock is present at every instant. In the above example, the current value of `x when c` is present when `x` and `c` are present and `c` is true. Since `x` and `c` are on the base clock `true`, the clock of `x when c` is noted `true on c`.

Consider the `sum` function which make the sum of its input (that is, $s_n = \Sigma_{i=0}^{n} x_i$).

```
let node sum x = s where rec s = x -> pre s + x
```

Now the `sum` function can be used at a slower rate by sampling its input stream:

```
let node sampled_sum x y = sum(x when y)

val sampled_sum :  int -> bool => int
val sampled_sum :: 'a -> (_c0:'a) -> 'a on _c0
```

`sampled_sum` has a function clock which follows its type structure. This clock type says that for any clock `'a`, if the first argument of the function has clock `'a` and the second argument named `_c0` has clock `a`, then the result is on clock `'a on _c0` (every expression variable is renamed in the clock to avoid name conflicts). An expression on clock `'a on _c0` is present when the clock `'a` is true and the boolean stream `_c0` is present and true.

Now, the sampled sum can be instantiated with an actual clock. For example:

```
(* a counter that counts modulo n *)
let node sample n =
  let rec cpt = 0 -> if pre cpt = n - 1 then 0 else pre cpt + 1
  and ok = cpt = 0 in
  ok

(* defining a 1/10 clock *)
let clock ten = sample 10

(* sampling a sum on 1/10 *)
let node sum_ten dx = sampled_sum dx ten

val ten :  bool
val ten_hz :: 'a
val sum_ten :  int => int
val sum_ten :: 'a -> 'a on ten
```

A clock name is introduced with the special keyword `clock` which builds a clock from a boolean stream.

Warning: Clocks provide a way to define control structures, that is, pieces of code which are executed according to some condition. It is thus important to understand their combination with delay operators as exemplified in the diagram below:

c	f	t	f	t	f	...
1	1	1	1	1	1	...
sum 1	1	2	3	4	5	...
(sum 1) when c		2		4		...
1 when c		1		1		...
sum (1 when c)		1		2		...
x	x_0	x_1	x_2	x_3	x_4	...
x when c		x_1		x_3		...
pre x	nil	x_0	x_1	x_2	x_3	...
pre (x when c)		nil		x_1		...
(pre x) when c		x_0		x_2		...

As soon as a function f contains some delay operator, sampling its inputs is not equivalent to sampling its outputs, that is, $f(x \texttt{ when } c) \neq (fx) \texttt{ when } c$.

Clocks can be arbitrarily nested. Consider, for example, the description of a (real) clock.

```
let clock sixty = sample 60
 let node hour_minute_second second =
  let minute = second when sixty in
  let hour = minute when sixty in
  hour,minute,second

val sixty :  bool
val sixty :: 'a
val hour_minute_second :  'a => 'a * 'a * 'a
val hour_minute_second :: 'a -> 'a on sixty on sixty * 'a on sixty * 'a
```

A stream on clock `'a on sixty on sixty` is only present one instant over 3600 instants which match perfectly what we are expecting.

Warning: We make a special treatment for clocks defined at top-level (as the clock `sixty`). A top-level clock is defined by a boolean expression (combinatorial or sequential) and is then considered as a constant process which can be instanciated several times. In the above program, they are two instanciations of the clock `sixty`: one is on some clock `'a` whereas the other run slowly at clock `'a on sixty`.

1.2.2 Combining Sampled Streams: the operator `merge`

`merge` conversely allows slow processes to communicate with faster ones by merging sub-streams into "larger" ones:

c	f	t	f	f	f	t	...
x		x_0				x_1	...
y	y_0		y_1	y_2	y_3		...
merge c x y	y_0	x_0	y_1	y_2	y_3	x_1	...

For instance, the `merge` allows us to define an "holding" function (the "current" operator of Lustre), which "holds" a signal between two successive samples (here `ydef` is a default value used before any sample has been taken):

```
let node hold ydef c x = y
    where rec y = merge c x ((ydef -> pre y) whenot c)

val hold :  'a -> bool -> 'a => 'a
val hold :: 'a -> (_c0:'a) -> 'a on _c0 -> 'a
```

c	f	t	f	f	f	t	...
x		x_0				x_1	...
y	y_0		y_1	y_2	y_3		...
ydef	d_0	d_1	d_2	d_3	d_4	d_5	...
hold c x ydef	d_0	x_0	x_0	x_0	x_0	x_1	...

Warning: Note the difference between `merge` and `if/then/else`. `merge` composes two complementary sequences and thus, has a lazy flavor. It is the data-flow version of the

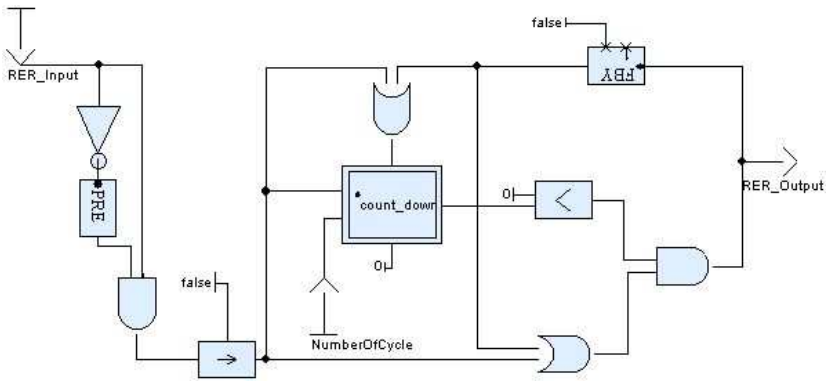


Figure 1.2: A classical operator in SCADE/LUSTRE

classical (lazy) conditional of sequential programming languages. The `if/then/else` is a strict operator which needs its three arguments to be on the same clock [2].

The following operator is a classical control engineering operator, available in both the SCADE/LUSTRE library and "digital" library of SIMULINK. Its graphical representation in SCADE/LUSTRE is given in figure 1.2. This operator detects a rising edge (false to true transition). The output becomes true as soon as a transition has been detected and remains unchanged during `number_of_cycle` cycles. The output is initially false and a rising edge occurring while the output is true is detected. In LUCID SYNCHRONE syntax, this is written [3]:

```
let node count_down (res, n) = cpt where
  rec cpt = if res then n else (n -> pre (cpt - 1))

let node rising_edge_retrigger rer_input number_of_cycle = rer_output where
    rec rer_output = (0 < v) & clk
    and v = merge clk (count_down ((count,number_of_cycle) when clk))
                      ((0 fby v) whenot clk)
    and c = false fby rer_output
    and clock clk = c or count
    and count = false -> (rer_input & pre (not rer_input))
```

1.2.3 Oversampling

Using clocks defined globally, we can write simple over-sampling functions, *i.e.* functions whose output has a larger rate than the input. One simple example is the stuttering function which computes the sequence $(o_n)_{n\in I\!N}$ such that:

$$o_{2n} = x_n$$
$$o_{2n+1} = x_n$$

It is written as follows:

[2] It corresponds to a `mux` in circuits.

[3] The `merge` construction is not provided in the current distribution of SCADE/LUSTRE (V5) and is replaced by an activation condition.

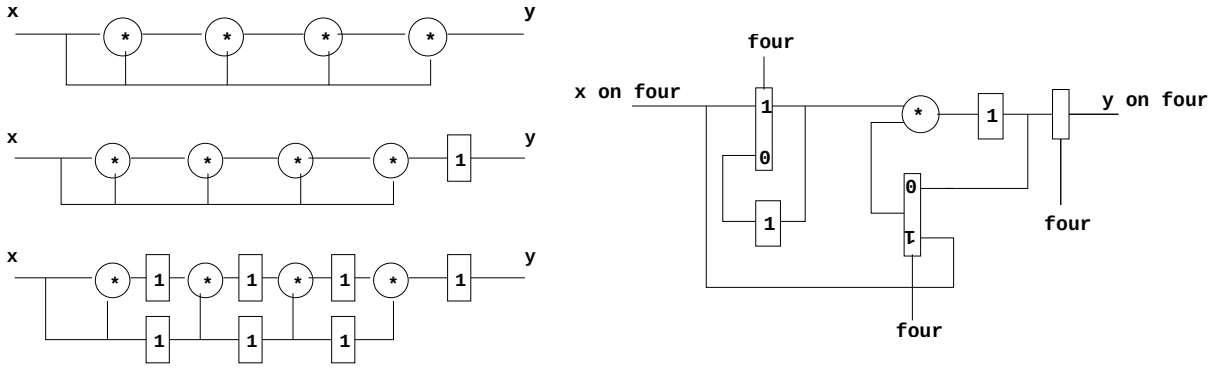


Figure 1.3: Duplication *vs* iteration for the computation of x^5

```
let clock half = h where rec h = true -> not (pre h)
let node over x = hold 1 half x
let node stuttering () =
  let rec nat = 0 -> pre nat + 1 in
  over nat

val half :  bool
val half :: 'a
val over :  int => int
val over :: 'a on half -> 'a
val stuttering :  unit => int
val stuttering :: 'a -> 'b
```

This is an example of oversampling, that is, a function whose internal clock (here `'a`) is *faster* than the clock of its input (here `'a on half`): the function `stuttering` computes some internal value whereas it does not receive any new input. It shows that some limited form of oversampling — which is possible in SIGNAL and not in LUSTRE — can be achieved.

Oversampling appear naturally in a system when considering program transformation and refinements. For example, when the architecture does not offer enough parallelism, we replace it by iteration and this has some consequence on the instant where the results become available. Consider, for example, the computation of the power of a sequence $(y_n)_{n\in\mathbb{N}}$ such that:

$$y_n = (x_n)^5$$

Supposing that the machine is able to execute four multiplications, we simply write:

```
let node spower x = y where y = x * x * x * x * x
let node shift_power x = y where y = 1 fby (x * x * x * x * x)

val spower :  int => int
val spower :: 'a -> 'a
val shift_power :  int => int
val shift_power :: 'a -> 'a
```

The graphical representation is given on the left of figure 1.3. The output is available at the same (logical) instant as the input is received and this is why the function gets clock

```
'a -> 'a.
```

`shift_power` is another version obtained by inserting a delay at the end of the computation. Now, a pipelined version can be obtained by a simple retiming transformation, leading to a speed-up of four in average.

```
let node ppower x = y where
  rec x2 = 1 fby x * x
  and px = 1 fby x
  and x3 = 1 fby x2 * px
  and ppx = 1 fby px
  and x4 = 1 fby x3 * ppx
  and pppx = 1 fby ppx
  and y = 1 fby x4 * pppx

val ppower :  int => int
val ppower :: 'a -> 'a
```

x	x_0	x_1	x_2	x_3	x_4	x_5	x_6	...
spower x	x_0^5	x_1^5	x_2^5	x_3^5	x_4^5	x_5^6	x_6^5	...
shift_power x	1	x_0^5	x_1^5	x_2^5	x_3^5	x_4^5	x_5^6	...
ppower x	1	1	1	1	x_0^5	x_1^5	x_2^5	...

Now, suppose that the machine has only one multiplier instead of four. Then, the value x_n^5 cannot be obtained in one cycle. We replace parallel computation by iteration, making the clock of `x` five times slower. The new system is given on the right of figure 1.3.

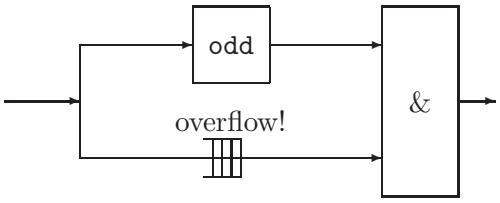
```
let clock four = sample 4

let node tpower x = y where
  rec i = merge four x ((1 fby i) whenot four)
  and o = 1 fby (i * merge four x (o whenot four))
  and y = o when four

val tpower :  int => int
val tpower :: 'a on four -> 'a on four
```

five	t	f	f	f	t	f	f	f	t	f	f	f	t	f	...
x	x_0				x_1				x_2				x_3		...
i	x_0	x_0	x_0	x_0	x_1	x_1	x_1	x_1	x_2	x_2	x_2	x_2	x_3	x_3	...
o	1	x_0^2	x_0^3	x_0^4	x_0^5	x_1^2	x_1^3	x_1^4	x_1^5	x_2^2	x_2^3	x_2^4	x_2^5	x_3^2	...
tpower x	1				x_0^5				x_1^5				x_2^5		...

`spower x` is a time refinement of the computation of `shift_power`, it produces the same sequence of values. We have made the internal clock faster than the input/output clock in order to exhibit every step of the computation.



x	x_0	x_1	x_2	x_3	x_4	x_5	x_6	...
half	t	f	t	f	t	f	t	...
x when half	x_0		x_2		x_4		x_6	...
x & (x when half)	$x_0 \,\&\, x_0$		$x_1 \,\&\, x_2$		$x_2 \,\&\, x_4$		$x_3 \,\&\, x_6$	...

Figure 1.4: A non Synchronous Example

As a consequence of the clock discipline and clock inference, using `tpower` in place of `shift_power` will automatically slowdown the whole system. This guaranty modular design, that is, `tpower` can be used anywhere `power` was previously used.

Remark: The current version of the compiler does not take the value of clocks into account (that is, it is unable to know that `four` is a periodic clock). such that it can ensure the equivalence between the various designs.

1.2.4 Clock constraints and error messages

Program must follow some clocking rules. For example, the and gate `(&)` expects its two arguments to be booleans and to be on the same clock, as expressed by the following signatures:

```
val (&) : bool -> bool -> bool
val (&) :: 'a -> 'a -> 'a
```

Thus, writting the following program leads to a clocking error:

```
let clock half = sample 2
let node odd x = x when half
let node wrong_clocked x = x & odd x
```

where `wrong_clocked x` combines the stream `x` to the sub-stream of `x` made by filtering one item over two. Thus it should compute the sequence $(x_n \& x_{2n})_{n \in \mathbb{N}}$. Note that this computation is clearly not bounded memory through it is only composed of bounded memory operators. The corresponding *Kahn network* [6] of `wrong_clocked x` is depicted in figure 1.4. Indeed `&` consumes one item of its two inputs in order to produce one item of its output. One of its two inputs is twice faster than the second one and, as time goes on, the number of successive values to store in a buffer will increase and the system will eventually stop. Whereas the sequence $(x_n \& x_{2n})_{n \in \mathbb{N}}$ is perfectly well defined, it will be considered as a *non synchronous* computation — its corresponding Kahn Network cannot be executed without buffering — and shall be statically rejected by the compiler. When given to the compiler, we get:

```
File "tutorial.ls", line 78, characters 31-36:
>let node wrong_clocked x = x & odd x
>                               ^^^^^
This expression has clock 'a on half,
but is used with clock 'a.
```

`x` gets clock `'b` whereas `odd x` gets clock `'b on half` and these two clocks cannot made be equal. Clock constraints in LUCID SYNCHRONE insure that the corresponding Kahn network can be executed without synchronization mechanisms using possibly unbounded buffering. This is why we reject it when dealing with real-time applications.

1.2.5 Equality and scope restrictions in the use of clocks

When a clock name is introduced with the `let clock` constructor, the name is considered to be unique and does not take into account the expression on the right-hand side of the `let clock`. Thus, the following program is rejected:

```
let node wrong () =
  let clock c = true in
  let v = 1 when c in
  let clock c = true in
  let w = 1 when c in
  v + w
```

and we get the following error:

```
File "tutorial.ls", line 62, characters 6-7:
>  v + w
>      ^
This expression has clock 'b on ?_c1,
but is used with clock 'b on ?_c2.
```

Because of the inference aspect of the clock calculus, some restriction are imposed on the use of clocks [4]. The main restriction is that it is not possible to return a value which depends on some clock computed locally [5].

When clocks are introduced with the `clock` constructions, these clock must not escape their lexical scope. For example:

```
let node within min max x = o where
  rec clock c = (min <= x) & (x <= max)
  and o = true when c

File "tutorial.ls", line 123-125, characters 4-75:
>....node within min max x = o where
> rec clock c = (min <= x) & (x <= max)
> and o = true when c
The clock of this expression, that is, 'b -> 'b on ?_c0
depends on ?_c0 which escape its scope.
```

[4] This may change in future versions.

[5] This is in contrast with version 1 or LUSTRE where it is possible to return a value depending on some clock c provided that c be also returned as a result.

This program is rejected because the `let clock` construction introduces a fresh clock name `?_c0` which abstract the exact value of `c`. This name must not exist already, that is, it must not appear in the clock of some existing variable when clocking the `let/clock` construct and it cannot escape its local scope. Here, the program is rejected since the function returns an expression on clock `'a on ?_c0` but `?_c0` must stay local to its block structure.

```
let node escape x =
  let clock c = true in
  merge c (x + (1 when c)) 0

File "tutorial.ls", line 123-125, characters 4-75:
>....node escape x =
>  let clock c = true in
>  merge c (x + (1 when c)) 0
The clock of this expression, that is, 'b on ?_c0 -> 'b
depends on ?_c0 which escape its scope.
```

The program is rejected because the variable `x` should already be on the clock `'a on ?_c0` in which `?_c0` appears. This fresh name must not escape the scope of the construction.

Remark: Thus, clocks introduced by the `clock` construction have a lifetime limited to their block. This is an important restriction of Lucid Synchrone V3 whose clock calculus is strictly less expressive than the one of V1. In this version (as well as in Lustre), a function may return a value sampled on some boolean value computed locally as soon as this value is also returned as an output. This allows to eliminate the first type of scope restriction. The program given above is simply written:

```
let node within min max x = (c, o) where
  rec clock c = (min <= x) & (x <= max)
  and o = true when c
```

Nonetheless, this is at a price of a more complex clock calculus and its usefullness in practice appeared to be questionnable. Moreover, one can often turn around this restriction by using signals as we shall see in section 1.5.

1.3 Static Values

Static values are infinite constant streams made of a value and they are introduced with the construction `let static`. Static values are usefull to define parameterised systems. For example:

```
let static m = 100.0
let static g = 9.81
let static mg = m *. g

val mg :  float
val mg :: static
```

A static value is distinguished from the other by its clock: the clock static means that the value can be computed once for all at instantiation time, before the execution starts.

It is possible to impose that the input of a function be a static value. For example:

```
let node integr (static dt) x0 dx = x where
  rec x = x0 -> pre x +. dx *. dt

val integr :  float -> float => float
val integr :: static -> 'a -> 'a
```

The definition of a static value is valid if the right-hand part of the definition is a constant stream. In the present version of the compiler, a stream is said to be constant when it is both combinatorial and its clock can be fully generalized.

A static expression is thus not necessarily an immediate constant. It can be any combinatorial expression which only depend on other static expressions. This is why the following program is rejected:

```
let node wrong x0 dt =
  integr (0.0 -> 1.0) x0 dt

File "tutorial.ls", line 15, characters 10-20:
>  integr (0.0 -> 1.0) x0 dt
>          ^^^^^^^^^^
This expression has clock 'b,
but is used with clock static.
```

1.4 Data-types, Pattern matching

1.4.1 Type definitions

Sum types, product types, and record types may be defined in the same way as in Objective Caml. The syntax is the one of Objective Caml. See the Objective Caml documentation for details and the present reference manual for syntactic considerations.

The first example defines a sum type `number`, with both integers and floating point numbers. The second one defines a type `circle`, representing a circle as a record containing a `center`, given by its coordinates, and a `radius`.

```
type number = Int of int | Float of float

type circle = { center: float * float; radius: float }
```

1.4.2 Pattern matching

The language provides means for doing pattern matching over streams with a `match/with` construction *à la* Objective Caml. This construction is a generalized form of the `merge` and thus, follows the same clocking rules.

Consider the example of a colored wheel rotating on an axis and for which we want to compute the rotation direction. This wheel is composed of three sections with colors blue (`Blue`), red (`Red`) and green (`Green`). A sensor observes the successive colors on the wheel and has to decide if the wheel is immobile or determine the rotation direction.

We consider that the direction is direct (`Direct`) when there is a succession of `Red`, `Green`, `Blue`, `Red`..., the opposite direction being indirect (`Indirect`). There are some instants where the direction is undetermined (`Undetermined`) or that the wheel is immobile (`Immobile`).

We program the controler in the following way. First, we introduce two sum types. The function `direction` then compares three successive values of the input stream `i`.

```
type color = Blue | Red | Green
type dir = Direct | Indirect | Undetermined | Immobile

let node direction i = d where
  rec pi = i fby i
  and ppi = i fby pi
  and match ppi, pi, i with
    (Red, Red, Red) | (Blue, Blue, Blue) | (Green, Green, Green) ->
         do d = Immobile done
  | (_, Blue, Red) | (_, Red, Green) | (_, Green, Blue) ->
         do d = Direct done
  | (_, Red, Blue) | (_, Blue, Green) | (_, Green, Red) ->
         do d = Indirect done
  | _ -> do d = Undetermined done
  end

val direction :  color => dir
val direction :: 'a -> 'a
```

The handler of a pattern-matching construct is made of a set of equations defining *shared* variables (here the variable `d`). At each instant, the `match/with` statement selects the first pattern (from top to bottom) which matches the actual value of the triple `pii, pi, i` and executes the corresponding branch. During a reaction, only one branch is executed.

Because only one branch is executed during a reactin, one must be careful when programming with such control structures, in particular in the presence of delay operators. This can be illustrated on the following program. This program is made of two modes: in the `Up` mode, the variable `o` increases by step `1` whereas in the mode `Down`, it decreases by step `-1`.

```
type modes = Up | Down

let node two m i = o where
  rec last o = i
  and match m with
        Up -> do o = last o + 1 done
      | Down -> do o = last o - 1 done
      end
```

The equation `last o = i` defines a shared memory `last o` which is initialized with the first value of `i`. `o` is called a shared variable because it is defined by several equations. When `m` equals `Up`, `o` equals `last o + 1`. When `m` equals `Down`, `o` equals `last o - 1`. The communication between the two modes is done through a shared memory `last o`. `last o` contains the previous value of `o`, the last time `o` has been defined. The execution diagram for some execution is given below.

i	0	0	0	0	0	0	0	...
m	Up	Up	Up	Down	Up	Down	Down	...
last o + 1	1	2	3		3			...
last o - 1				2		2	1	...
o	1	2	3	2	3	2	1	...
last o	0	1	2	3	2	3	2	...

This program is equivalent to the following one:

```
type modes = Up | Down

let node two m i = o where
  rec last_o = i -> pre o
  and match m with
        Up -> do o = last_o + 1 done
      | Down -> do o = last_o - 1 done
      end
```

making clear that `last o` stands for the previous defined value of `o`.

Warning: Whereas `last o` may seem to be just another way to refer to the previous value of a stream like `pre o` does, there is a fundamental difference between the two. This difference is a matter or instant of observation.

- In data-flow systems (e.g., block diagram design *à la* Simulink or Scade/Lustre), `pre` *e* stands for a local memory, that is, `pre` denotes the last value of its argument, the last time it was *computed*. If `pre` *e* appear in a block structure which is executed from time to time — say on some clock *ck* — it means that the argument *e* is only computed when *ck* is true.
- `last` *o* denotes the previous value of the variable *o* on the instant where the variable *o* is *defined*. `last` *o* is only valid when *o* stands for a variable and not an expression. `last` *o* is useful to communicate values between modes and this is why we call it a shared memory.

We illustrate the difference between the two on the following example. We now compute two other streams `c1` and `c2` returning respectively the number of instants each mode is active.

```
let node two m i = (o, c1, c2) where
  rec last o = i
  and last c1 = 0
  and last c2 = 0
  and match m with
        Up -> do o = last o + 1
              and c1 = 1 -> pre c1 + 1
              done
      | Down -> do o = last o - 1
                and c2 = 1 -> pre c2 + 1
                done
    end
```

The equation `c1 = 1 -> pre c1 + 1` is only active in the `Up` mode whereas equation `c2 = 1 -> pre c2 + 1` is active in mode `Down`. The execution diagram is given below.

i	0	0	0	0	0	0	0	...
m	Up	Up	Up	Down	Up	Down	Down	...
last o + 1	1	2	3		3			...
1 -> pre c1 + 1	1	2	3		4			...
last o - 1				2		2	1	...
1 -> pre c2 + 1				1		2	3	...
o	1	2	3	2	3	2	1	...
last o	0	1	2	3	2	3	2	...
c1	1	2	3	3	4	4	4	...
c2	0	0	0	1	1	2	3	...

A pattern matching composes several complementary sub-streams, that is, streams on complementary clocks. The above pattern matching has two branches. Every branch defines its own clock, one denoting the instants where `m = Up` and the other denoting the instant where `m = Down`.

1.4.3 Local Definitions

It is possible to define variables which stay local to a branch. For example:

```
let node two m i = o where
  match m with
    Up -> let rec c = 0 -> pre c + 1 in
          do o = c done
  | Down -> do o = 0 done
  end
```

1.4.4 Implicit Definition of Shared Variables

Finally, note that the branches of a pattern-matching constraint do not have to contain a definition for all the shared variables. Shared variables are implicitely completed by adding an equation of the form `x = last x`in branches which they are not defined. Nonetheless, the compiler rejects program for which it cannot guaranty that the last value is defined. Thus, the following program is statically rejected.

```
let node two m i = o where
  rec match m with
        Up -> do o = last o + 1 done
      | Down -> do o = last o - 1 done
      end
File "test.ls", line 9, characters 21-31:
>        Up -> do o = last o + 1 done
>                     ^^^^^^^^^^
This expression may not be initialised.
```

1.5 Valued Signals

The language provides a way to manage *valued signals*. Signals are built and accessed through the construction `emit` and `present`. A value signal is a pair made of (1) a boolean stream c indicating when the signal is present and (2) a stream sampled on that clock c [6]. In circuit terminology, we get circuits with enable.

1.5.1 Signals as Clock Abstraction

Signals can be built from sampled streams by abstracting their internal clock. Consider again the example given in section 1.2.5. This program can now be accepted if we write:

```
let node within min max x = o where
  rec clock c = (min <= x) & (x <= max)
  and emit o = true when c

val within :  'a -> 'a -> 'a => bool sig
val within :: 'a -> 'a -> 'a -> 'a sig
```

It computes a condition `c` and a sampled stream `true when c`. The equation `emit o = true when c` defines a signal `o` which is present and equal to `true` when `c` is true. The `emit` construction can be considered as a boxing mechanism which pack a value with its clock condition. The right part of the construction `emit` must be an expression with some clock type a `on` c. In that case, it defines a signal with clock type a `sig`.

1.5.2 Testing the Presence and Signal Matching

It is possible to test for the presence of a signal expression e by writting the boolean expression $?e$. The following program, for example, counts the number of instants where `x` is emitted.

```
let node count x = cpt where
  rec cpt = if ?x then 1 -> pre cpt + 1 else 0 -> pre cpt

val count :  'a sig => int
val count :: 'a sig -> 'a
```

The language provides a more general mechanism to test for the presence of several signals and access their values. It is reminiscent of the pattern-matching construct of ML. This pattern matching mechanisn is safe in the sense that it is possible to access the value of a signal only at the instant where it is emitted. This is in contrast with ESTEREL, for example, where the value of a signal implicitly holds and can be accessed even when it is not emitted.

The following program takes two signals `x` and `y` and returns an integer which equals the sum of `x` and `y` when both are emitted, it returns the value of `x` when `x` is emitted only and the value `0` when only `y` is emitted and `0` otherwise.

[6] In type notation, a signal is a dependent pair with clock type $\Sigma(c : a).a$ `on` c.

```
let node sum x y = o where
  present
    x(v) & y(w) -> do o = v + w done
  | x(v1) -> do o = v1 done
  | y(v2) -> do o = v2 done
  | _ -> do o = 0 done
  end

val sum :  int sig -> int sig => int
val sum :: 'a sig -> 'a sig -> 'a
```

A `present` statement is made of several signal conditions and handlers. Each condition is tested sequentially. The signal condition `x(v) & y(w)` is verified when both signals `x` and `y` are present. A condition `x(v1)` means "`x` is present and has some value `v1`". The variable `v1` can in turn be used in the corresponding handler. The last signal condition `_` stands for the wildcard signal condition which is always verified.

In the signal pattern `x(v) & y(w)`, `x` and `y` are expressions evaluating to signal values whereas `v` and `w` stand for patterns. Thus, writting `x(42) & y(w)` would mean: "await for the presence of signal `x` evaluating to `42` and the presence of `y`.

Note that the output of the function `sum` is a regular flow since the test is exhaustive. Forgetting the default case will raise an error.

```
let node sum x y = o where
  present
    x(v) & y(w) -> do o = v + w done
  | x(v1) -> do o = v1 done
  | y _ -> do o = 0 done
  end

File "test.ls", line 6-10, characters 2-105:
>..present
>    x(v) & y(w) -> do o = v + w done
>  | x(v1) -> do o = v1 done
>  | y _ -> do o = 0 done
>  end
The identifier o should be defined in every handler or given a last value.
```

We can easily eliminate this error by giving a last value to `o` (e.g., adding an equation `last o = 0` outside of the present statement). In that case, the default case is implicitly completed with an equation `o = last o`. The other way is to state that `o` is now a signal and is thus only partially defined.

```
let node sum x y = o where
  present
    x(v) & y(w) -> do emit o = v + w done
  | x(v1) -> do emit o = v1 done
  | y _ -> do emit o = 0 done
  end

val sum :  int sig -> int sig => int sig
val sum :: 'a sig -> 'a sig -> 'a sig
```

A signal pattern may also contain boolean expressions. The following program, sums the values of the two signals `x` and `y` provided they arrive at the same time and `z >= 0`.

```
let node sum x y z = o where
  present
    x(v) & y(w) & (z >= 0) -> do o = v + w done
  | _ -> do o = 0 done
  end
```

Remark: Using signals, we can mimic the `default` construction of the language SIGNAL. `default x y` emits the value of `x` when `x` is present and the value of `y` when `x` is absent and `y` is present.

```
let node default x y = o where
  present
    x(v) -> do emit o = v done
  | y(v) -> do emit o = v done
  end
```

This is, of course, only a simulation since all the information about clocks has been lost. In particular, the compiler is unable to state that `o` is emitted only when `x` or `y` are present as the clock calculus of SIGNAL does for the default operator.

In some circumstances, it can be valuable to prefer sampling operators `when` and `merge` in order to benefit from clock information.

1.6 State Machines

The language provides means to define state machines, as a way to describe directly control dominated systems. These state machines can be composed in parallel with regular equations or other state machines and can be arbitrarily nested.

In this tutorial, we first consider state machines where transitions are only made of boolean expressions. Then, we consider two important extensions of the basic model. The first one is the ability to build define state machines with parameterized states. The second one introduces the general form of transitions made of signal matching and boolean expressions.

An automaton is a collection of states and transitions. A state is made of a set of equations in the spirit of the *Mode-automata* by Maraninchi & Rémond. Two kinds of transitions are provided, namely *weak* and *strong* transitions and for each of them, it is possible to enter in the next state by *reset* or by *history*. One important feature of these state machines is that *only one set of equations is executed during one reaction.*

1.6.1 Strong Preemption

Here is a two state automaton illustrating strong preemption. The function `expect` awaits `x` to be true and emits `true` for the remaining instants.

```
(* await x to be true and then sustain the value *)
let node expect x = o where
  automaton
    S1 -> do o = false unless x then S2
  | S2 -> do o = true done
  end

val expect :  bool => bool
val expect :: 'a -> 'a
```

This automaton is made of two states, each of them defining the value of a *shared* variable `o`. The keyword `unless` indicates that `o` is defined by the equation `o = false` from state `S1` while `x` is false. At the instant where `x` is true, `S2` becomes the active state for the remaining instant. Thus, the following chronogram hold:

x	false	false	true	false	false	true	...
expect x	false	false	true	true	true	true	...

1.6.2 Weak Preemption

On the contrary, the following function emits `false` at the instant where `x` is true and `true` for the remaining instants, thus corresponding to regular *Moore automata*.

```
(* await x to be true and then sustain the value *)
let node expect x = o where
  automaton
    S1 -> do o = false until x then S2
  | S2 -> do o = true done
  end

val expect :  bool => bool
val expect :: 'a -> 'a
```

x	false	false	true	false	false	true	...
expect x	false	false	false	true	true	true	...

The classical two states `switch` automaton can be written like the following:

```
let node weak_switch on_off = o where
  automaton
    False -> do o = false until on_off then True
  | True -> do o = true until on_off then False
  end
```

Note the difference with the following form with weak transitions only:

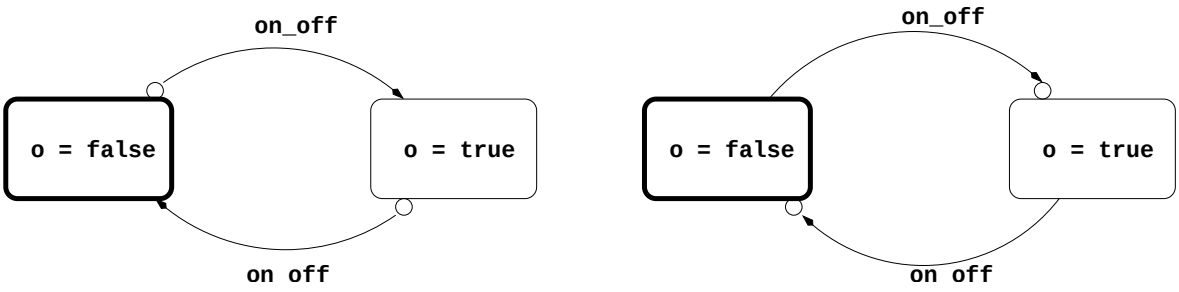


Figure 1.5: Two automata with strong and weak transitions

```
let node strong_switch on_off = o where
  automaton
    False -> do o = false unless on_off then True
  | True -> do o = true unless on_off then False
  end
```

We can check that for any boolean stream `on_off`, the following property holds:

```
weak_switch on_off = strong_switch (false -> pre on_off)
```

The graphical representation of these two automata is given in figure 1.5.

Weak and strong conditions can be arbitrarily mixed as in the following variation of the switch automaton:

```
let node switch2 on_off stop = o where
  automaton
    False -> do o = false until on_off then True
  | True -> do o = true until on_off then False unless stop then Stop
  | Stop -> do o = true done
  end
```

Compared to the previous version, state `True` can be strongly preempted when some stop condition `stop` is true.

1.6.3 ABRO and Modular Reseting

The ABRO example is due to Gérard Berry [2]. It highlight the expressive power of parallel composition and preemption in Esterel. The specification is the following:

> Awaits the presence of events `A` and `B` and emit `O` at the exact instant where both events have been received. Reset this behavior every time `R` is received.

Here is how we write it, replacing capital letters by small letter [7].

[7] As in Objective Caml, identifiers starting with a capital letter are considered to be constructors and cannot be used for variables.

```
(* emit o and sustain it when a and b has been received *)
let node abo a b = (expect a) & (expect b)

(* here is ABRO: the same except that we reset the behavior *)
(* when r is true *)
let node abro a b r = o where
  automaton
    S1 -> do o = abo a b unless r then S1
  end
```

The node `abro` is a one state automaton which *resets* the computation of `abo a b`: every stream in `abo a b` restarts with its initial value. The language provides a specific `reset/every` primitive as a shortcut of such a one-state automaton and we can write:

```
let node abro a b r = o where
  reset
    o = abo a b
  every r
```

The `reset/every` construction combines a set of parallel equations (separated with an `and`). Note that the reset operation correspond to strong preemption: the body is reseted at the instant where the condition is true. The language does not provide a "weak reset". Nonetheless, it can be easily obtained by inserting a delay as illustrated below.

```
let node abro a b r = o where
  reset
    o = abo a b
  every true -> pre r
```

1.6.4 Local Definitions in a State

It is possible to define names which are local to a state. These names can only be used inside the body of the state and may be used in weak conditions only.

The following programs integrates the integer sequence `v` and emits false until the sum has reached some value `max`. Then, it emits `true` during `n` instants.

```
let node consumme max n v = status where
  automaton
    S1 ->
      let rec c = v -> pre c + v in
      do status = false
      until (c = max) then S2
  | S2 ->
      let rec c = 1 -> pre c + v in
      do status = true
      until (c = n) then S1
  end
```

State `S1` defines a local variable `c` which can be used to compute the weak condition `c = max` and this does not introduce any causality problem. Indeed, weak transitions are only effective during the next reaction, that is, they define the next state, not the current one. Moreover, there is no restriction on the kind of expressions appearing in conditions and they may, in particular, have some internal state. For example, the previous program can be rewritten as:

```
let node counting v = cpt where
  rec cpt = v -> pre cpt + v

let node consumme max n v = status where
  automaton
    S1 ->
       do status = false
       until (counting v = max) then S2
  | S2 ->
       do status = true
       until (counting 1 = n) then S1
  end
```

The body of a state is a sequence (possibly empty) of local definitions (with `let/in`) followed by some definitions of shared names (with `do/until`). As said previously, weak conditions may depend on local names and shared names.

It is important to notice that using `unless` instead of `until` leads to a *causality error*. Indeed, in a strong preemption, the condition is evaluated *before* the equations of the body and thus, cannot depend on them. In a weak preemption, the condition is evaluated at the end, *after* the definitions of the body have been evaluated. Thus, when writting:

```
let node consumme max n v = status where
  automaton
    S1 ->
      let rec c = v -> pre c + v in
      do status = false
      unless (c = max) then S2
  | S2 ->
      let rec c = 1 -> pre c + v in
      do status = true
      unless (c = n) then S1
  end
```

The compiler emits the message:

```
File "tutorial.ls", line 6:
> unless c = max then S2
>        ^^^^^^^
This expression may depend on itself.
```

1.6.5 Communication between States and Shared Memory

In the previous examples, there is no communication between values computed in each state. Consider a simple system made of two running modes as seen previously. In the `Up` mode, the system increases some value with a fixed step `1` whereas in the `Down` mode, this value decreased with the same step. Now, the transition from one mode to the other is described by a two-state automaton whose behavior depends on the value computed in each mode. This example, due to Maraninchi & Rémond [8] can be programmed in the following way.

```
let node two_states i min max = o where
  rec automaton
        Up -> do
                o = last o + 1
              until (o = max) then Down
      | Down -> do
                  o = last o - 1
                until (o = min) then Up
      end
  and last o = i
```

An execution diagram is given below:

i	0	0	0	0	0	0	0	0	0	0	0	0	...
min	0	0	0	0	0	0	0	0	0	-1	0	0	...
max	4	4	4	4	4	4	4	4	4	4	4	4	...
last o	0	1	2	3	4	3	2	1	0	-1	0	1	...
o	1	2	3	4	3	2	1	0	-1	0	1	2	...
last o + 1	1	2	3	4						0	1	2	...
last o - 1					3	2	1	0	-1				...

1.6.6 The Particular Role of the Initial State

The initial state can be used for defining some variables whose value can then be sustained in remaining states. In that case, their last value is considered to be defined. Moreover, it becomes possible not to define their value in all the states.

```
let node two_states i min max = o where
  rec automaton
        Init ->
           do o = i until (i > 0) then Up
      | Up ->
          do o = last o + 1
          until (o = max) then Down
      | Down ->
          do o = last o - 1
          until (o = min) then Up
      end
```

i	0	0	0	1	1	1	1	1	1	1	1	1	1	1	...
min	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	...
max	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	...
last o	0	0	0	0	1	2	3	4	3	2	1	0	-1	0	1	...
o	0	0	0	1	2	3	4	3	2	1	0	-1	0	1	2	...
last o + 1	0	0	0	1	2	3	4						0	1	2	...
last o - 1	0	0	0					3	2	1	0	-1				...

Because the initial state `Init` is only weakly preempted, `o` is necessarily initialized with the current value of `i`. Thus, `last o` is well defined in the remaining states. Note that replacing the weak preemption by a strong one will lead to an error.

```
let node two_states i min max = o where
  rec automaton
        Init ->
          do o = i unless (i > 0) then Up
      | Up ->
          do o = last o + 1
          until (o = max) then Down
      | Down ->
          do o = last o - 1
          until (o = min) then Up
      end
```

and we get:

```
File "tutorial.ls", line 128, characters 20-30:
>                 o = last o + 1
>                     ^^^^^^^^^^
This expression may not be initialised.
```

We said previously that strong conditions must not depend on some variables computed in the current state but they can depend on some shared memory `last o` as in:

```
let node two_states i min max = o where
  rec automaton
        Init ->
          do o = i until (i > 0) then Up
      | Up ->
          do o = last o + 1
          unless (last o = max) then Down
      | Down ->
          do o = last o - 1
          unless (last o = min) then Up
      end
```

and we get the same execution diagram as before:

i	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	...
min	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	...
max	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	...
last o	0	0	0	0	1	2	3	4	3	2	1	0	-1	0	1	...
o	0	0	0	1	2	3	4	3	2	1	0	-1	0	1	2	...
last o + 1	0	0	0	1	2	3	4						0	1	2	...
last o - 1	0	0	0					3	2	1	0	-1				...

Note that the escape condition `do x = 0 and y = 0 then Up` in the initial state is a shortcut for `do x = 0 and y = 0 until true then Up`.

Finally, `o` do not have to be defined in all the states. In that case, it keeps its previous value, that is, an equation `o = last o` is implicitely added.

1.6.7 Resume a Local State

By default, when entering in a state, every computation in the state is reseted. We also provides some means to resume the internal memory of a state (this is called *enter by history* in UML diagrams).

```
let node two_modes min max = o where
  rec automaton
        Up -> do o = 0 -> last o + 1 until (o >= max) continue Down
      | Down -> do o = last o - 1 until (o <= min) continue Up
      end
```

min	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	...
max	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	...
o	0	-1	0	1	2	3	4	3	2	1	0	-1	0	1	2	...

This is an other way to write *activation conditions* and is very convenient for programming a scheduler which alternate between some computations, each of them keeping its own state as in:

```
let node time_sharing c i = (x,y) where
  rec automaton
        Init ->
          do x = 0 and y = 0 then S1
      | S1 ->
          do x = 0 -> pre x + 1 until c continue S2
      | S2 ->
          do y = 0 -> pre y + 1 until c continue S1
      end
```

1.7 Parameterized State Machines

In the examples we have considered so far, an automaton is made of a finite set of states and transitions. It is possible to define more general state machines containing parameterized states, that is, states that may be initialized with some input values. Parameterized states

are a natural way to pass informations from states to states and to reduce the number of states. A full section is dedicated to automata with parameterized states because as they lead to a different style of programming.

The following program is a simple counter that counts the number of occurrences of `x`:

```
let node count x = o where
  automaton
    Zero -> do o = 0 until x then Plus(1)
  | Plus(v) -> do o = v until x then Plus(v+1)
  end
```

This automaton simulates an infinite state machine with states `Zero`, `Plus(1)`, `Plus(2)`, etc.

We now come back to the example of the mouse controller whose informal specification is reminded below:

> Return the event `double` when two `click` has been received in less than four `top`.
> Emits `simple` if only one click has been received.

This specification is too informal and says nothing about the precise instant where `double` or `simple` must be emitted. The mouse controller can be programmed as a three states automaton:

```
let node counting e = cpt where
  rec cpt = if e then 1 -> pre cpt + 1 else 0 -> pre cpt

let node controler click top = (simple, double) where
  automaton
    Await ->
     do  simple = false and double = false
     until click then One
  | One ->
     do  simple = false and double = false
     unless click then Emit(false, true)
     unless (counting top = 4) then Emit(true, false)
  | Emit(x1, x2) ->
     do simple = x1 and double = x2
     until true then Await
  end
```

It first awaits for the first occurrence of `click`, then it enters in state `One`, starting to count the number of `top`. This state can be preempted strongly when a second `click` occurs or that the condition `counting top = 4` is true. For example when `click` is true, the control immediately enters in state `Emit(false, true)`, giving the initial values `false` to `x1` and `true` to `x2`. Thus, at the same instant, `simple = false` and `double = true`. Then, the control goes to the initial state `Await` at the next instant.

This example illustrates an important feature of automata in Lucid Synchrone: only one set of equations is active during a reaction but it is possible to compose (at most) one strong preemption followed by a weak preemption during on reaction. This is precisely what we made in the previous example. As opposed to other formalisms (e.g., StateCharts) it is impossible to cross an arbitrary number of states during a reaction.

1.8 State Machines and Signals

In the automata we have considered so far, conditions on transitions are boolean expressions. The language provides a more general mechanism allowing to test (and access) signals on transitions.

Using signals, we can reprogram the mouse controller in the following way.

```
type e = Simple | Double

let node controler click top = o where
  automaton
    Await ->
     do until click then One
  | One ->
     do unless click then Emit Double
     unless (counting top = 4) then Emit Simple
  | Emit(x) ->
     do emit o = x
     until true then Await
  end

val controler :  bool -> bool => e sig
val controler :: 'a -> 'a -> 'a sig
```

Note that nothing is emitted in states `Await` and `One`. It should normally raise an error (in the existing form of automata). By writting `emit o = x`, we state that `o` is a signal and not a regular stream. We do not impose `o` to be defined in every branch (and to complement it with its last value). Here, the signal `o` is only emitted in state `Emit`. Otherwise, it is considered to be absent.

The use of signals combined with sum type has some advantage here with respect to the use of boolean variables in the previous version of the mouse controller. By construction, only three values are possible for the output of the system: `o` can be `Simple`, `Double` or absent. In the previous version, a fourth case corresponding to the boolean value `simple & double` was possible, even though it does not make sense.

1.8.1 Pattern Matching over Signals

Now, we must consider how signals are accessed. We generalize conditions to be signal patterns as provided by the `present` statement.

Let us consider a system with two input signals `low`, `high` and an output integer stream `o`.

```
let node switch low high = o where
  rec automaton
        Init -> do o = 0 until low(u) then Up(u)
      | Up(u) ->
          do o = last o + u
          until high(v) then Down(v)
      | Down(v) ->
          do o = last o - v
          until low(w) then Up(w)
      end

val switch :  'a sig -> 'a sig => 'a
val switch :: 'a sig -> 'a sig -> 'a
```

The condition `until low(w)` says: *await for the presence of the signal* `low` *with some value* `w`. *Then go to the parameterized state* `Up(w)`.

The right part of a pre-emption condition is of the form $e(p)$ where e is an expression of type t `sig` and p stands for a pattern of type t. The condition is a binder: the pattern p is bound with the value of the signal at the instant where e is present. In the above example, it introduces the variable `w`. It is also possible to test for the presence of a signal as well as the validity of a boolean condition. For example:

```
let node switch low high = o where
  rec automaton
    Init -> do o = 0 until low(u) then Up(u)
  | Up(u) ->
      let rec timeout = 0 -> pre timeout + 1 in
      do o = last o + u
      until high(v) & (timeout > 42) then Down(v)
  | Down(v) ->
      let rec timeout = 0 -> pre timeout + 1 in
      do o = last o - v
      until low(w) & (timeout > 42) then Up(w)
  end

val switch :  'a sig -> 'a sig => 'a
val switch :: 'a sig -> 'a sig -> 'a
```

The system has the same behavior except that the presence of `high` in the `Up` state is only taken into account when the `timeout` stream has reached the value `42`.

Finally, we can write a new version of the mouse controller where all the values are signals.

```
type e = Simple | Double

let node counting e = o where
  rec o = if ?e then 1 -> pre o + 1 else 0 -> pre o

let node controler click top = e where
  automaton
    Await ->
     do until click(_) then One
  | One ->
     do unless click(_) then Emit Double
     unless (counting top = 4) then Emit Simple
  | Emit(x) ->
     do emit e = x
     then Await
  end

val controler :  'a sig -> 'b sig => 'c sig
val controler :: 'a sig -> 'a sig -> 'a sig
```

1.8.2 The derived operator `await/do`

The operator `await/do` is a built-in operator which allows to await for a the presence of a signal. This is a short-cut for a two states automaton. For example:

```
(* emits nothing while x is not present *)
(* then start counting from the received value *)
let node counting x = o where
  automaton
    Await -> do unless x(v) then Run(v)
  | Run(v) -> let rec cpt = v -> pre cpt + 1 in
      do emit o = cpt done
  end
```

This can be written as:

```
let node counting x =
  await x(v) do
  let rec cpt = v -> pre cpt + 1 in
  cpt

val counting :  int sig => int
val counting :: 'a sig -> 'a
```

We end with a function which awaits for the n-th occurrence of a signal and returns a signal made of the value received at the instant. We write it in two different ways:

```
let node nth n s = o where
  rec cpt = if ?s then 1 -> pre cpt + 1 else 0 -> pre cpt
  and o = await s(x) & (cpt = n) do x
```

Awaiting the second occurrence of a signal `s` can be written:

```
let node second s = await (nth 2 s)(v) do v
```

1.9 Alternative Syntax for Control Structures

We can notice that the three control structures (`match/with`, `automaton` and `present`) combine equations. Each branch is made of a set of equations defining shared values. In this form, it is not necessary to give a definition for each shared variable in all the branches: a shared variable implicitely keeps its previous value or is absent if it is defined as a signal.

We have adopted this syntactical convention to be close to the graphical representation of programs in synchronous dataflow tools (such as SCADE/LUSTRE). In such tools, control structures naturally combine (large) sets of equations and the implicit completion of absent definitions is essential.

The language also provides a derived form for control structures allowing them to be used as expressions. For example:

```
let node expect x =
  automaton
    Await -> false unless x then One
  | One -> true
  end
```

is a short-cut for:

```
let node expect x =
  let automaton
        Await -> do o = false unless x then One
      | One -> do o = true done
      end in
  o
```

In the same way:

```
let node two x =
  match x with
    true -> 1
 | false -> 2
 end
```

as a short-cut for:

```
let node two x =
  let match x with
        true -> do o = 1 done
     | false -> do o = 2 done
     end in
  o
```

thus leading to a more conventional notation for the OBJECTIVE CAML programmer.

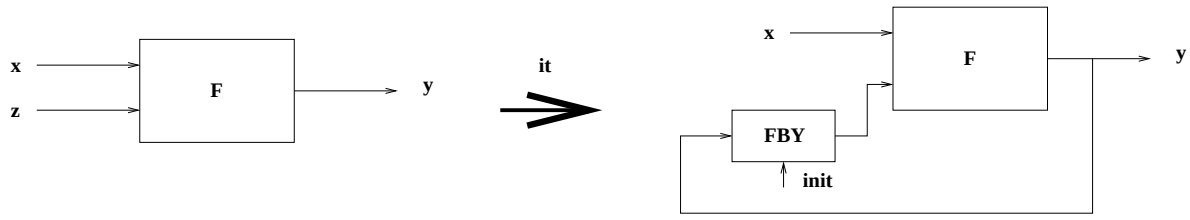


Figure 1.6: A rewinding operator

1.10 Higher-order Reactive Features

1.10.1 Composing Functions

The language is a functional language: functions are first-class objects which can be given to functions or returned by functions. For example, the `it` function feeds back a network (i.e, it iterates a function on a stream of values). It graphical representation is given in figure 1.6.

```
let node it f init x = y where
  rec y = f x (init fby y)

val it : ('a -> 'b -> 'b) -> 'b -> 'a => 'b
val it :: ('a -> 'b -> 'b) -> 'b -> 'a -> 'b
```

such that:

```
sum x = it (+) 0 x
```

Note that type signature of `it` states that its argument `f` is considered to be a combinatorial function. To make a (more general) rewinding operator for a stateful function, one has to write instead:

```
let node it f init x = y where
  rec y = run (f x) (init fby y)

val it : ('a -> 'b => 'b) -> 'b -> 'a => 'b
val it :: ('a -> 'b -> 'b) -> 'b -> 'a -> 'b
```

The `run` keyword used in an expression states that its argument is expected to be a stateful function. Thus, `run (f x)` indicates that `f x` must have some type $t_1 \Rightarrow t_2$ instead of $t_1 \rightarrow t_2$.

Higher-order is a natural way to build new primitives from existing ones. For example, the so-called "activation condition" is a build-in operator in block-diagram design tools (*à la* SCADE/LUSTRE or SIMULINK). An activation condition takes a function `f`, a clock `clk`, a `default` value and an `input` an computes `f(input when clk)`. It then sets the result on the base clock.

```
let node cond_act f clk default input =
  let rec o =
    merge clk (run f (input when clk))
              ((default fby o) whenot clk) in
  o

node cond_act :  ('a => 'b) -> bool -> 'b -> 'a -> 'b
node cond_act :: ('a on _c0 -> 'a on _c0) -> (_c0:'a) -> 'a -> 'a -> 'a
```

Using the `cond_act` construction, one can rewrite the `RisingEdgeRetrigger` operator given in section 1.2.2 as the following:

```
let node count_down (res, n) = cpt where
  rec cpt = if res then n else (n -> pre (cpt - 1))

let node rising_edge_retrigger rer_input number_of_cycle = rer_output where
    rec rer_output = (0 < v) & clk
    and v = cond_act count_down clk 0 (count, number_of_cycle)
    and c = false fby rer_output
    and clock clk = c or count
    and count = false -> (rer_input & pre (not rer_input))
```

The symmetric operation of the activation condition is an *iterator* which simulates an internal `for` or `while` loop, generalizing what has been done in paragraph 1.2.3. This operator consists in iterating a function on an input.

```
let node iter clk init f input =
    (* read input when clk is true *)
    let rec i = merge clk input ((init fby i) whenot clk) in
    let rec o = f i po
    and po = merge clk (init when clk) ((init fby o) whenot clk) in
    (* emit output when clk is true *)
    o when clk

val iter :  clock -> 'a -> ('a -> 'a -> 'a) -> 'a => 'a
val iter :: (_c0:'a) -> 'a -> ('a -> 'a -> 'a) -> 'a on _c0 -> 'a on _c0
```

`iter clk init f input` reads an `input` every time `clk` is true and computes `f`. The computation takes place at every instant (on clock `'a`) whereas `input` is read only when `clk` is true.

We can illustrate this operator on the computation of the power of a sequence. Let `x` be some stream with clock `'a on clk` such that the number of instants between two successive true values of `clk` is k. Now, write a program which computes the sequence $(y_i)_{i\in I\!N}$ such that $y_0 = 1$ and $y_{i+1} = x_i^{k_i}$.

clk	t	f	f	t	f	t	f	f	f	t	t	...
x	x_0			x_1		x_2				x_3	x_4	...
k	1	2	3	1	2	1	2	3	4	1	1	...
y	1			x_0^3		x_1^2				x_2^4	x_3	...

This program can be implemented in the following way:

```
let node power clk x = o where
    o = iter clk 1 (fun i acc -> i * acc) x

let node power10 x = power ten x
```

1.10.2 Combinators

Here are some typical combinators.

```
let node (||) f g x = (run f x, run g x)

let node (>) f g x = run g (run f x)

let clock half = h where rec h = true -> not (pre h)

let node alternate f g x = merge half (run f (x when half))
                                      (run g (x whenot half))

val || :  ('a => 'b) -> ('a => 'c) -> 'a => 'b * 'c
val || :: ('a -> 'b) -> ('a -> 'c) -> 'a -> 'b * 'c
val > :  ('a => 'b) -> ('b => 'c) -> 'a => 'c
val > :: ('a -> 'b) -> ('b -> 'c) -> 'a -> 'c
val half :  bool
val half :: 'a
val alternate :  ('a => 'b) -> ('a => 'b) -> 'a => 'b
val alternate ::
  ('a on half -> 'b on half) ->
  ('a on not half -> 'b on not half) -> 'a -> 'b
```

The infix operator `(||)` computes the product of two functions `f` and `g` and `(>)` composes two functions. `alternate` alternates the execution of a function with another one.

All the programs defined above still define reactive systems: programs are compiled into finite state machines answering in bounding time and space whatever be their input.

1.10.3 Streams of Functions and Functions of Streams

In the examples considered previously, function used as parameters do not evolve during the execution. Intuitively, the `it` function receives a stream function `f` and instantiates it once.

The language provides some means to deal with streams of functions. This is strictly more expressive that the previous case and is a way to model *reconfigurable* systems.

1.10.4 Instantiating Streams of Functions

The function application instantiates a function with some argument. We can define a more general operator, say `reconfigure` which expects a stream of function `code`, an argument and instantiates the current value of the code every time a new code is received.

```
let node reconfigure code input = o where
  rec automaton
        Await -> do unless code(c) then Run(c)
      | Run(c) -> do emit o = c input unless code(c) then Run(c)
      end
```

We can make the example a little more complicated by bounding the time for computing `c input`. For example:

```
let node server code input money = o where
  automaton
    Await ->
      do unless code(c) & money(m) then Run(c,m)
  | Run(c,m) ->
      let rec cpt = m -> pre cpt - 1 in
      do emit o = c input
      until (cpt = 0) then Await
  end
```

1.11 Non reactive higher-order features

Besides this functional facility, we can also define recursive functions, such as the celebrated Eratosthenes sieve:

```
let node first x = v
  where rec v = x fby v

let rec node sieve x =
  let clock filter = (x mod (first x))<> 0
  in  merge filter
            (sieve (x when filter))
            (true fby false)

let node from n = o where rec o = n fby (o + 1)

let clock sieve = sieve (from 2)

let node primes () = (from 2) when sieve
```

```
val first :  'a => 'a
val first :: 'a -> 'a
val sieve :  int => bool
val sieve :: 'a -> 'a
val from :  int => int
val from :: 'a -> 'a
val sieve :  bool
val sieve :: 'a
val primes :  unit => int
val primes :: 'a -> 'b on sieve
```

This program is no more real-time since the time and memory to answer at every instant grows.

A compilation option `-realtime` is provided for restricting the language to define only real-time programs.

Here is another way of writing the same program using the implicit filtering of streams done by the pattern matching construct:

```
let rec node sieve x =
  let filter = (x mod (first x))<> 0 in
  match filter with
    true -> sieve x
  | false -> true fby false
  end

let node primes () =
  let nat = from 2 in
  let clock ok = sieve n in
  let emit o = n when ok in
  o
```

```
val sieve :  int => bool
val sieve :: 'a -> 'a
val primes :  unit => int sig
val primes :: 'a -> 'b sig
```

Note that in these two versions, the absence of unbounded instantaneous recursion is somehow hidden: the program is reactive because the very first value of `filter` is false. Here is a guarded version where no instantaneous recursion can occur.

```
let rec node sieve x =
  automaton
    Await -> true then Once(x)
  | Once(i) ->
      match not_divides_l i x with
        true -> sieve x
      | false -> false
      end
  end
```

Chapter 2

Complete Examples

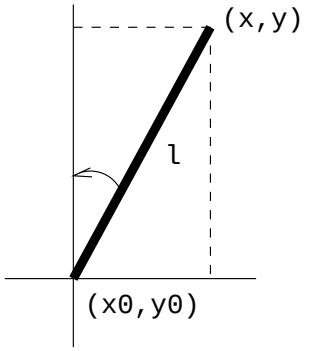
We end this tutorial introduction with some typical examples. The first one is the *inverted pendulum* which can be programmed in a purely data-flow style. The second one is a simple controller for a personal gas heater and illustrate the combination of data-flow equations and state machines. The next one is a simple version of the coffee machine as defined by Milner in [9] and adapted from Kevin Hammond description written in Hume [5]. We end with a recursive description of a N-buffer. These examples show the compilation and communication with the host language [1].

Other examples are available in the distribution of the language.

2.1 The Inverted Pendulum

Consider the problem of balancing an inverted pendulum with the hand (through a mouse). The inverted pendulum has a length l, its bottom has coordinates x_0 and y_0 which are continuously controlled by the user and it forms an angle θ with the vertical. This pendulum is submitted to the following law:

$$\texttt{l} \times \frac{d^2\theta}{dt^2} = (sin(\theta) \times (\frac{d^2\texttt{y0}}{dt^2} + g)) - (cos(\theta) \times \frac{d^2\texttt{x0}}{dt^2})$$
$$\texttt{x} = \texttt{x0} + \texttt{l} \times sin(\theta)$$
$$\texttt{y} = \texttt{y0} + \texttt{l} \times cos(\theta)$$



We suppose that some auxiliary scalar functions have been defined in a Objective Caml module `Draw` with implementation `draw.ml` and interface `draw.mli`. A pendulum is characterized by its bottom and top coordinates. The exported values are defined below:

```
(* file draw.mli *)
type pendulum
```

[1] The full source code of the examples is available in the distribution.

```
val make_pend : float -> float -> float -> float -> pendulum
val clear_pend : pendulum -> unit
val draw_pend : pendulum -> unit
val mouse_pos : unit -> float * float
```

We start by defining a synchronous module for integrating and deriving a signal.

```
(* file misc.ls *)
(* rectangle integration *)
let node integr t dx = let rec x = 0.0 -> t *. dx +. pre x in x

(* derivative *)
let node deriv t x = 0.0 -> (x -.(pre x))/. t
```

Now, the main module defines global constants and the pendulum law.

```
(* file pendulum.ls *)
open Draw
open Misc

let static t = 0.05 (* sampling frequency *)
let static l = 10.0 (* length of the pendulum *)
let static g = 9.81 (* acceleration *)

let node integr dx = Misc.integr t dx
let node deriv x = Misc.deriv t x

(* the equation of the pendulum *)
let node equation d2x0 d2y0 = theta
where
  rec theta =
      let thetap = 0.0 fby theta
      in integr (integr ((sin thetap) *. (d2y0 +. g)
                         -.(cos thetap) *. d2x0) /. l)

let node position x0 y0 =
  let d2x0 = deriv (deriv x0)  in
  let d2y0 = deriv (deriv y0)  in

  let theta = equation d2x0 d2y0 in

  let x = x0 +. l *. (sin theta)  in
  let y = y0 +. l *. (cos theta)  in
  make_pend x0 y0 x y
```

As in Objective Caml, an `open` *Module* directive makes the names exported by the module *Module* visible in the current module [2]. Imported values may be either used with the dot

[2]The implemented module system of Lucid Synchrone is borrowed from Caml Light, giving the minimal tools for importing names from Objective Caml files or from Lucid Synchrone files.

notation (e.g, `Draw.mouse_pos`) or directly (e.g, `make_pend`) once the module is opened.

Finally the main function continuously reads informations from the mouse, computes the position of pendulum, clear its previous position and draw its current position. We get:

```
let node play () =
  let x0,y0 = mouse_pos () in
  let p = position x0 y0 in
  clear_pendulum (p fby p);
  draw_pendulum p;;
```

Now, all the files must be compiled. The compiler of Lucid Synchrone acts as a preprocessor: the compilation of the implementation `misc.ls` produces a file `misc.ml` and a compiled interface `misc.lci` containing informations about types and clocks of the implementation. Similarly, the compilation of the scalar interface `draw.mli` produces a compiled interface `draw.lci`. Files are compiled by typing:

```
% lucyc draw.mli          => draw.lci
% lucyc misc.ls           => misc.ml, misc.lci
% lucyc pendulum.ls       => pendulum.ml
% lucyc -s play -sampling 0.05 pendulum.lci

% ocamlc draw.mli
% ocamlc draw.ml
% ocamlc pendulum.ml
% ocamlc play.ml
% ocamlc -o play draw.cmo pendulum.cmo play.cmo ...
```

The whole system is obtained by linking all the modules (synchronous and scalars ones) and by sampling the main transition function `play` on a timer (here, 0.05 seconds) giving the base clock (the real-time clock) of the system.

2.2 The Heater

Consider the problem of a system which control a gas heater as informally depicted in figure 2.1.

The heater front has a green light indicating a normal functioning whereas the red light is turned on when some problem has occurred (security stop). In that case, the heater is stopped and it can be restarted by pushing a restart button. Moreover, a rotating button allows the user to indicate the expected temperature of the water.

The controller has thus the following inputs.

- `restart` is used to restart the heater.
- `expected_temp` is the expected temperature of the water. The heater is expected to maintain this temperature.
- `actual_temp` is the actual temperature of the water measured by a sensor.
- `light_on` indicates that the light is on (that is, the gas is burning)

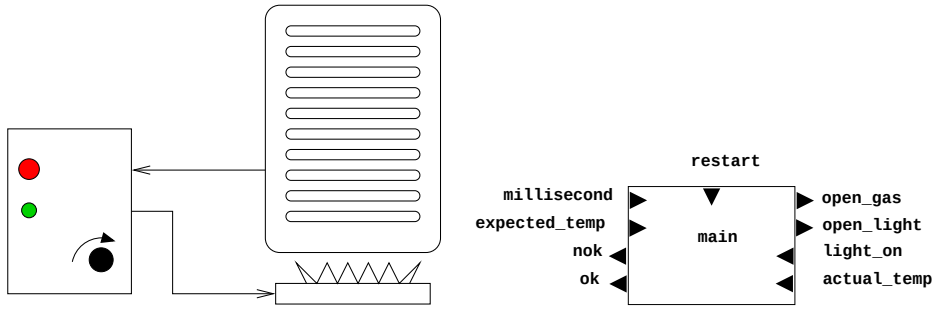


Figure 2.1: The heater

- `millisecond` is a boolean flow given the clock of the system.

The outputs of the controller are the following:

- `open_light` opens the light command.
- `open_gas` opens the valve for the gas.
- `ok` indicate the status of the heater (controlling the green light) whereas `nok` indicates a problem (thus controlling the red light). Only the `restart` button can restart the heater.

The purpose of the controller is to keep the water temperature close to the expected temperature. Moreover, when this temperature must be heated, the controller turns on the gas and light for at most `500` millisecond. When the light is on, only the gas valve is maintained open. If there is no light after `500` millisecond, it stops for `100` millisecond and start again. If after three tests, there is still no light, the heater is blocked on a security stop. Only pushing the `restart` button allows to start again the process.

We start with the definition of a few scalar constants and two auxiliary functions.

```
let static low = 4
let static high = 4

let static delay_on = 500 (* in miliseconds *)
let static delay_off = 100

(* [count d t] returns [true] when [d] occurrences of [t] has been received *)
let node count d t = ok where
  rec ok = cpt = 0
  and cpt = d -> if t & not (pre ok) then pre cpt - 1 else pre cpt

let node edge x = false -> not (pre x) & x
```

The following node decides weather the heater must be turn on. We introduce an hysteresis mechanism to avoid oscillation. `low` and `high` are two threshold. The first version is a purely data-flow one whereas the second one (which is equivalent) uses the automaton construction.

```
(* controling the heat *)
(* returns [true] when [expected_temp] does not agree with [actual_temp] *)
let node heat expected_temp actual_temp = ok where
  rec ok = if actual_temp <= expected_temp - low then true
           else if actual_temp >= expected_temp + high then false
           else false -> pre ok

(* the same function using two modes *)
let node heat expected_temp actual_temp = ok where
  rec automaton
        False ->
          do ok = false
          unless (actual_temp <= expected_temp - low) then True
      | True ->
          do ok = true
          unless (actual_temp >= expected_temp + high) then False
      end
```

Now, we define a node which turns on the light and gas for 500 millisecond then turn them off for 100 millisecond and restarts.

```
(* a cyclic two mode automaton with an internal timer *)
(* [open_light = true] and [open_gas = true] for [delay_on millisecond] *)
(* then [open_light = false] and [open_gas = false] for *)
(* [delay_off millisecond] *)
let node command millisecond = (open_light, open_gas) where
  rec automaton
        Open ->
          do open_light = true
          and open_gas = true
          until (count delay_on millisecond) then Silent
      | Silent ->
          do open_light = false
          and open_gas = false
          until (count delay_off millisecond) then Open
      end
```

The program which control the aperture of the light and gas is written below:

```
(* the main command which control the opening of the light and gas *)
let node light millisecond on_heat on_light = (open_light, open_gas, nok) where
  rec automaton
        Light_off ->
          do nok = false
          and open_light = false
          and open_gas = false
          until on_heat then Try
```

```
      | Light_on ->
          do nok = false
          and open_light = false
          and open_gas = true
          until (not on_heat) then Light_off
      | Try ->
          do
            (open_light, open_gas) = command millisecond
          until light_on then Light_on
          until (count 3 (edge (not open_light))) then Failure
      | Failure ->
          do nok = true
          and open_light = false
          and open_gas = false
          done
      end
```

Finally, the main function connects the two parts.

```
(* the main function *)
let node main millisecond restart expected_temp actual_temp on_light =
                                        (open_light, open_gas, ok, nok) where
  rec reset
        on_heat = heat expected_temp actual_temp
      and
        (open_light, open_gas,nok) = light milisecond on_heat on_light
      and
        ok = not nok
      every restart
```

Supposing that the program is written in a file `heater.ls`, the program can be compiled by typing:

```
% lucyc -s main heater.ls
```

which produces files `heater.ml` and `main.ml`, the later containing the transition function for the node `main`.

2.3 The Coffee Machine

The following example is inspired from the Coffee Machine introduced by Milner in his CCS book [9].

The description is the following. The machine may serve coffee or tea. A tea costs ten cents whereas a coffee costs five. The user may enter dimes or nickels. He can select a tea, a coffee or ask for his money back.

```
type coin = Dime | Nickel
```

```
type drinks = Coffee | Tea
type buttons = BCoffee | BTea | BCancel


(* emits a drink if the accumulated value [v] is greater than [cost] *)
let node vend drink cost v = (o1, o2) where
  match v >= cost with
    true ->
      do emit o1 = drink
      and o2 = v - cost
      done
  | false ->
      do o2 = v done
  end
```

Now we define a function which output a drink and return some money when necessary.

```
let node coffee coin button = (drink, return) where
  rec last v = 0
  and present
        coin(Nickel) ->
          do v = last v + 5 done
      | coin(Dime) ->
          do v = last v + 10 done
      | button(BCoffee) ->
          do (drink, v) = vend Coffee 10 (last v)
          done
      | button(BTea) ->
          do (drink, v) = vend Tea 5 (last v)
          done
      | button(BCancel) ->
          do v = 0
          and emit return = last v
          done
      end
```

The function `coffee` can be also written like the following.

```
let node coffee coin button = (drink, return) where
  rec last v = 0
  and present
        coin(w) ->
          do match w with
               Nickel -> do v = last v + 5 done
             | Dime -> do v = last v + 10 done
             end
          done
      | button(b) ->
```

```
          do match b with
               BCoffee -> do (drink, v) = vend Coffee 10 (last v) done
             | BTea -> do (drink, v) = vend Tea 5 (last v) done
             | BCancel -> do v = 0 and emit return = last v done
             end
          done
       end
```

We end by adding the code for simulating the whole system.

```
(* producing events from the keyboard *)
let node input key = (coin, button) where
  match key with
    "N" -> do emit coin = Nickel done
  | "D" -> do emit coin = Dime done
  | "C" -> do emit button = BCoffee done
  | "T" -> do emit button = BTea done
  | "A" -> do emit button = BCancel done
  | _ -> do done
  end

(* printing things *)
let print_drink d =
  match d with
    Coffee -> print_string "Coffee\n"
  | Tea -> print_string "Tea\n"
  end

let print_coin d =
  match d with
    Nickel -> print_string "Nickel\n"
  | Dime -> print_string "Dime\n"
  end

let print_button d =
  match d with
    BCoffee -> print_string "BCoffee\n"
  | BTea -> print_string "BTea\n"
  | BCancel -> print_string "BCancel\n"
  end

let node print f e =
  present
    e(x) -> f x
  | _ -> ()
  end
```

```
let node output drink return =
   print print_drink drink;
   print print_int return

let node main () =
  let key = read_line () in
  let (coin, button) = input key in
  let drink, return = coffee coin button in
  output drink return
```

The final application is obained by typing:

```
%lucyc -s main -sampling 0 coffee.ls
%ocamlc -o main coffee.ml main.ml
```

2.4 The Recursive Wired Buffer

The following example illustrates the combination of synchrony and recursion. We program a buffer by composing several instances of a one place buffer [3].

A one-place buffer is defined in the following way. In doing it, it is important that the one-place buffer emits its internal values when it is full and receives a push in order to pass it to its son.

```
type 'a option = None | Some of 'a

let node count n = ok where
  rec o = 0 -> (pre o + 1) mod n
  and ok = false -> o = 0

(* the 1-buffer with bypass *)
let node buffer1 push pop = o where
  rec last memo = None
  and match last memo with
      None ->
        do present
            push(v) & pop() -> do emit o = v done
          | push(v) -> do memo = Some(v) done
        end done
    | Some(v) ->
        do present
            push(w) -> do emit o = v and memo = Some(w) done
          | pop() -> do emit o = v and memo = None done
        end done
  end
```

[3] This corresponds to a hardware implementation and is certainly not a good way to implement it in software since pushing or poping a value is in $O(n)$ for a n-place buffer. A more efficient version (which can also be programmed in Lucid Synchrone) stores values in a circular array.

The n-buffer is the composition of n one-place buffers.

```
(* the recursive buffer *)
let rec node buffer n push pop = o where
  match n with
      0 ->
        do o = push done
    | n ->
        let pusho = buffer1 push pop in
        do
          o = buffer (n-1) pusho pop
        done
  end

(* the main buffer function only responds when it receives a pop *)
let node buffer n push pop = o where
  rec pusho = buffer n push pop
  and present
        pop() & pusho(v) -> do emit o = v done
      | _ -> do done
      end

let node sbuffer (static n) push pop = buffer n push pop
```

Part II

Reference manual

Chapter 3

The language

The language is built on top of Objective Caml [7], an ML language developed at INRIA. Many parts of this reference manual are common to Objective Caml and are borrowed from its reference manual, with the permission of the author. The present document should be used in complement with the Objective Caml reference manual.

The syntax of the language is given in BNF-like notation. Terminal symbols are set in typewriter font (`like this`). Non-terminal symbols are set in italic font (*like that*). Square brackets [...] denote optional components. Curly brackets { ... } denotes zero, one or several repetitions of the enclosed components.

3.1 Lexical conventions

Lexical conventions for blanks, comments, identifiers, integer literals, floating-point literals, character literals, string literals, prefix and infix symbols are the one of Objective Caml.

Keywords

The following identifiers are keywords.

```
let  and   if    then  pre   or   node  done      unless   run   end
rec  where fun   else  not   open match automaton continue emit
when fby   merge reset every do   ntil  on        await
```

The following character sequences are also keywords:

```
->   >     <     =     <>     >=       )     &  ?
+    -     *     /     ;;     <=       (     .
```

3.2 Values

3.2.1 Basic values

Lucid Synchrone only implements the basic values of Objective Caml with the same convention, that is, integer numbers, floating-point numbers, characters and character strings.

3.2.2 Tuples, records, sum types

Lucid Synchrone implements the tuples of Objective Caml, with the same conventions. It also implements records and sum types.

Functions and nodes

Mapping from values to values. Functions are stateless mapping whereas nodes denote possibly stateful values.

3.3 Global names

The naming conventions in Lucid Synchrone are inherited from Objective Caml with some restrictions [1]. They are listed here:

Names in Lucid Synchrone are decomposed into the following syntactic classes:

- The syntactic class *value-name* for value names
- The syntactic class *typeconstr-name* for type constructors
- The syntactic class *module-name* for module names

3.3.1 Naming values

value-name	::=	*lowercase-ident*
	|	`(` *operator-name* `)`
operator-name	::=	*prefix-symbol* | *infix-symbol* | `*` | `=` | `or` | `&`
constructor-name	::=	*capitalized-ident*
	|	`()`
typeconstr-name	::=	*lowercase-ident*
module-name	::=	*capitalized-ident*

As in Objective Caml, the syntactic class of *lowercase-ident* is the set of identifiers starting with a lowercase letter whereas *capitalized-ident* is the set of of identifiers starting with a capital letter.

3.3.2 Referring to named values

value-path	::=	*value-name*
	|	*module-name* `.` *value-name*
constructor	::=	*constructor-name*
	|	*module-name* `.` *capitalized-ident*
typeconstr	::=	*typeconstr-name*
	|	*module-name* `.` *typeconstr*

A value can be referred either by its name or by qualifying the name with a module name.

[1] In fact, the naming convention are closer to the one of Caml Light but the adopted syntax is the one of Objective Caml.

3.4 Types

type ::= ' *ident*
| (*type*)
| *type* -> *type*
| *type* {* *type*}
| *type typeconstr*
| (*type* {, *type* }) *typeconstr*
| *typeconstr*

Their precedence rules are the one of OBJECTIVE CAML.

3.5 Clocks

clock ::= ' *ident*
| (*clock*)
| *stream-clock*
| (*carrier-clock* : *stream-clock*)
| (*clock* { * *clock* })
| *clock* sig
| static

stream-clock ::= ' *ident*
| (*stream-clock*)
| *stream-clock* on *carrier-clock*
| *stream-clock* on not *carrier-clock*

carrier-clock ::= *value-path*
| (*carrier-clock*)
| _ *ident*

The precedences are given in the following table. The constructions with higher precedences come first.

Operator	Associativity
sig	-
on	-
:	-
*	-
->	right

Clock variable

' *ident* denotes the clock variable *ident*.

Parenthesized clock

(*clock*) stands for *clock*.

Stream clock

The clock *stream-clock* is the presence information of a stream.

Sub-clock

The stream clock *stream-clock* `on` *carrier-clock* denotes the sub-clock of *stream-clock* when *carrier-clock* is true. The stream clock *stream-clock* `on not` *carrier-clock* denotes the sub-clock of *stream-clock* when *carrier-clock* is false.

Named clock

The clock `(` *carrier-clock* `:` *stream-clock* `)` of a stream e means that e has value *carrier-clock* which has the stream clock *stream-clock*. The value may be either a global value (defined at top-level) or an identifier. This identifier is unique and is an abstraction of the actual value of e.

Signal clock

The clock *clock* `sig` of a stream e means that e is a signal. A signal boxes a value with its internal clock indicating when the value is present.

Static clock

The clock `static` of a value e means that e can be computed at instantiation time, that is, before the execution starts. A variable defined with a static clock can thus be used at any clock.

Tuple clock, function clock

The clock `(` $clock_1$ `*` ... `*` $clock_n$ `)` is the clock of expressions evaluating to `(` v_1`,` ... `,` v_n `)` where v_i is on clock $clock_i$. The clock $clock_1$ `->` $clock_2$ is the clock of a function whose argument is on clock $clock_1$ and result on clock $clock_2$.

3.6 Constants

$$
\begin{array}{rcl}
\textit{immediate} & ::= & \textit{integer-literal} \\
& | & \textit{float-literal} \\
& | & \textit{char-literal} \\
& | & \textit{string-literal} \\
& | & \textit{boolean-literal}
\end{array}
$$

Constants are made of literals from the firth base types (integers, floating-point numbers, characters, character strings and booleans).

3.7 Patterns

pattern ::= *ident*
| `(` *pattern* `)`
| *pattern* `as` *ident*
| `_`
| *pattern* `,` *pattern* { `,` *pattern* }
| `()`
| *immediate*
| *constructor*
| *constructor pattern*
| { *label* `=` *pattern* { `;` *label* `=` *pattern* } }
| *clock ident*
| `static` *ident*

Patterns allow selecting data structures of a given shape and binding identifiers to components of the data structure. The meaning of pattern is the one given by Objective Caml.

3.8 Signal Patterns

signal-pattern ::= *simple-expr*
| *simple-expression pattern*
| *signal-pattern* `&` *signal-pattern*

Signal patterns allows to test the presence of signals and to match their value with some pattern. Moreover, a signal pattern can be also a boolean expression.

3.9 Expressions

simple-expr ::= *value-path*
| *constructor*
| *constructor expr*
| *immediate*
| `(` *expr* `)`
| { *label* `=` *expr* { `;` *label* `=` *expr* } }
| *simple-expr* `.` *label*

multiple-matching ::= *pattern-list* `->` *expr*
| *pattern-list* `=>` *expr*

pattern-list ::= *pattern* { *pattern* }

expr ::= *simple-expr*
| *simple-expr simple-expr* { *simple-expr* }
| `fun` *multiple-matching*
| *simple-expr* `where` [`rec`] *definition* { `and` *definition* }
| `let` [`rec`] *definition* { `and` *definition* } `in` *expr*
| `if` *expr* `then` *expr* `else` *expr*
| *prefix-op expr*
| *expr infix-op expr*
| *expr* `or` *expr*
| `not` *expr*
| *expr* `when` *expr*
| *expr* `whenot` *expr*
| `merge` *expr expr expr*
| *expr* `fby` *expr*
| `pre` *expr*
| `last` *ident*
| *expr* `->` *expr*
| `run` *simple-expr* { *simple-expr* }
| `await` *signal-pattern* `do` *expr*
| `match` *expr* `with` *match-handlers* `end`
| `reset` *expr* `every` *expr*
| `automaton` *automaton-handlers* `end`
| `present` *present-handlers* `end`

match-handlers ::= [`|`] *pattern* `->` *expr* { `|` *pattern* `->` *expr* }

present-handlers ::= [`|`] *signal-pattern* `->` *expr* { `|` *signal-pattern* `->` *expr* }

automaton-handlers ::= [`|`] *automaton-handler* { `|` *automaton-handler* }

automaton-handler ::= *constructor* [*pattern*] `->` *expr transitions*

transitions ::= ϵ
| `then` *state-expression*
| `continue` *state-expression*
| *transition* { *transition* }

transition ::= `until` *signal-pattern* `then` *state-expression*
| `until` *signal-pattern* `continue` *state-expression*
| `unless` *signal-pattern* `then` *state-expression*
| `unless` *signal-pattern* `continue` *state-expression*

The precedence and associativity rules are the one of Objective Caml. For special Lucid Synchrone primitives, they are given below: higher precedences come first.

`run`	left
`last`	right
`pre`	-
function application	right
`fby`	left
`when`, `whenot`	left
`merge`	left
... `let`,...	-
`->`	right

3.9.1 Simple expressions

Constants

Expressions consisting in a constant evaluate to an infinite stream made of this constant.

Variables

Expressions consisting in a variable evaluate to the value bound to this variable in the current evaluation environment.

Parenthetised expressions

The expression `(` *expr* `)` has the same value than *expr*.

Function abstraction

A function abstraction has two forms:

`fun` $pattern_1$ ... $pattern_n$ `->` *expr*

defines a *combinatorial* (or state-less) function. This means that expression *expr* must not contain any state constructions.

`fun` $pattern_1$ ... $pattern_n$ `=>` *expr*

defines a *sequential* (or state-full) function.

Function application

The expression $expr_1$ $expr_2$ is an application. The expression $expr_1$ must evaluate to a functional value which is applied to the value of $expr_2$.

The expression $expr_1$ $expr_2$ ... $expr_n$ stands for (...($expr_1$ $expr_2$) ... $expr_n$). No evaluation order is specified.

When $expr_1$ is a function imported from the host language Objective Caml and $expr_2$ is a stream then $expr_1$ $expr_2$ stands for the point-wise application of $expr_1$ to every element of $expr_2$.

Local definitions

The `let` and `let rec` constructs bind variables locally. The expression

$$\texttt{let}\ \mathit{definition}_1\ \texttt{and}\ \ldots\ \texttt{and}\ \mathit{definition}_n\ \texttt{in}\ \mathit{expr}$$

defines values to be visible in *expr*.

Recursive definitions of variables are introduced by `let rec`:

$$\texttt{let rec}\ \mathit{definition}_1\ \texttt{and}\ \ldots\ \texttt{and}\ \mathit{definition}_n\ \texttt{in}\ \mathit{expr}$$

Reverse local definition

The language provides an alternate form of local definitions written in a reverse order and borrowed from Caml Light. In this way, functions may be defined is a way similar to Lustre. The expression:

$$\mathit{simple\text{-}expr}\ \texttt{where}\ [\ \texttt{rec}\ ]\ \mathit{definition}_1\ \texttt{and}\ \ldots\ \texttt{and}\ \mathit{definition}_n$$

has the meaning of:

$$\texttt{let}\ [\ \texttt{rec}\ ]\ \mathit{definition}_1\ \texttt{and}\ \ldots\ \texttt{and}\ \mathit{definition}_n\ \texttt{in}\ \mathit{expr}$$

3.9.2 Operators

The operators written *infix-op* in the grammar can appear in infix position (between two expressions). The operators written *prefix-op* in the grammar (section 3.9 can appear in prefix position (in front of an expression).

Classical operators provided by Objective Caml (from the `Pervasives` module) are imported. As for general scalar value imported from the host language, they become stream operators which are applied point-wisely to streams.

Delays

The expression `pre` *expr* is the delayed stream. *expr* must be a stream. The clock of the result is the clock of *expr*. The n-th value of the result is the $n-1$-th value of *expr*. Its value at the first instant is undefined.

The binary operator `fby` is the initialized delay operator. The first value of $expr_1$ `fby` $expr_2$ is the first value of $expr_1$. Its n-th value is the $n-1$-th value of $expr_2$.

Shared Memory

The expression `last` *ident* denotes a shared memory which contains the last computed value of *ident*.

Initialization

$expr_1$ `->` $expr_2$ initializes a stream. The $expr_i$ must be streams of the same type and on the same clock. It returns a stream with the same type and clock. The first value of the result is the first value of $expr_1$. Then, the n-th value of the result is the n-th value of $expr_2$.

Point-wise conditional

The expression `if` $expr_1$ `then` $expr_2$ `else` $expr_3$ is the point-wise conditional. $expr_1$ must be a boolean stream, $expr_2$ and $expr_3$ two streams of the same type. The type of the result is the type of $expr_2$. The expressions $expr_i$ must be on the same clock. The clock of the result is the clock of $expr_1$. The conditional returns a stream such that its n-th value is the n-th value of $expr_2$ if the n-th value of $expr_1$ is true and the n-th value of $expr_3$ otherwise.

Under-sampling

The expression $expr_1$ `when` $expr_2$ is the under-sampling operator. $expr_1$ must be a stream and $expr_2$, a clock made from a boolean stream. The type of the result is the type of $expr_1$. The expressions $expr_i$ must be on the same clock cl. The clock of the result is a sub-clock cl `on` $expr_2$. This expression returns the sub-stream of $expr_1$ defined for all instants where $expr_2$ is defined and is true.

Over-sampling

The expression `merge` $expr_1$ $expr_2$ $expr_3$ merges two complementary streams. $expr_1$ must be a boolean stream, $expr_2$ and $expr_3$ two streams of the same type. The type of the result is the type of $expr_2$. If $expr_1$ is on clock cl, $expr_2$ must be on clock cl `on` $expr_1$ ($expr_2$ must be present when $expr_1$ is present and true) and $expr_3$ must be on clock cl `on not` $expr_1$. This expression returns a stream such that its n-th value is the n-th value of $expr_2$ if the n-th value of $expr_1$ is true and the n-th value of $expr_3$ otherwise.

3.9.3 Control Structures

The constructions `reset`, `match/with`, `reset` and `automaton` are control-structures which combine equations and thus belong to the syntactic class of definitions (see section 3.10).

A derived form belonging to the syntactic class of expressions is also provided. The derived form is useful for textual programming whereas the original one is motivated by the graphical representation of dataflow programs. The derived form is only syntactic sugar for the original form.

Awaiting Signals

The expression `await` *spat* `do` *expr* awaits for the presence of a signal before executing the expression *expr*. This construction is a short-cut for the expression:

```
let automaton
    | Await -> do unless spat then Go(v)
    | Go(v) -> do emit o = expr done
    end in
o
```

provided o is a fresh name and v is the list of free variables from the signal pattern *spat*.

Pattern Matching

The expression `match` *expr* `with` pat_1 `->` $expr_1$ `|` ... `|` pat_n `->` $expr_n$ `end` is a short-cut for the expression:

```
let match expr with
    | pat_1 -> do o = expr_1 done
    ...
    | pat_n -> do o = expr_n done
    end in
o
```

provided *o* is a fresh name.

Modular Reset

The expression `reset` $expr_1$ `every` $expr_2$ is a short-cut for `let reset` *o* `=` $expr_1$ `every` $expr_2$ `in` *o*, provided *o* is a fresh name.

Automata

The expression `automaton` $state_1$ `->` $expr_1$ $trans_1$ `|` ... `|` $state_n$ `->` $expr_n$ $trans_n$ `end` is a short-cut for the expression:

```
let automaton
   | state_1 -> do o = expr_1 trans_1
   ...
   | state_n -> do o = expr_n trans_n
   end in
o
```

provided *o* is a fresh name.

Testing the Presence

The expression `present` $spat_1$ `->` $expr_1$ `|` ... `|` $spat_n$ `->` $expr_n$ `end` is a short-cut for the expression:

```
let present
    | spat_1 -> do o = expr_1 done
    ...
    | spat_n -> do o = expr_n done
    end in
o
```

provided *o* is a fresh name.

3.10 Definitions

let-binding ::= *pattern* `=` *expr*
| *ident pattern-list* `=` *expr*
| `node` *ident pattern-list* `=` *expr*
| `last` *ident* `=` *expr*
| `emit` *ident* `=` *expr*

infix-op ::= *infix-symbol* | `*` | `=` | `or` | `&`

definition ::= *let-binding*
| `match` *expr* `with` *def-match-handlers* `end`
| `reset` *definition* { `and` *definition* } `every` *expr*
| `automaton` *def-automaton-handlers* `end`
| `present` *def-present-handlers* `end`

definition-list ::= [*definition* { `and` *definition* }]
| ϵ

local-definitions ::= { `let` [`rec`] *definition* { `and` *definition* } `in` }

def-match-handlers ::= [`|`] *def-match-handler* { `|` *def-match-handler* }

def-match-handler ::= *pattern* `->` *action*

action ::= *local-definitions* `do` *definition-list* `done`

def-automaton-handlers ::= [`|`] *def-automaton-handler* { `|` *def-automaton-handler* }

def-automaton-handler ::= *constructor* [*pattern*] `->` *automaton-action*

automaton-action ::= *local-definitions* `do` *definition-list def-transitions*

def-transitions ::= `done`
| `then` *state-expression*
| `continue` *state-expression*
| *transition* { *transition* }

state-expression ::= *constructor*
| *constructor* `(` *expr* `)`

def-present-handlers ::= [`|`] *def-present-handler* { `|` *def-present-handler* }
def-present-handler ::= *signal-pattern* `->` *action* `done`
| `_` `->` *action* `done`

Value Definition

A definition *pattern* `=` *expr* defines variables and is obtained by matching the value of *expr* with *pattern*. An alternate syntax is provided to define functional values. The definition:

$$ident \texttt{ = fun } pattern_1 \ ... \ pattern_n \texttt{ -> } expr$$

can be declared in the following way:

$$ident \ pattern_1 \ ... \ pattern_n \texttt{ = } expr$$

And the definition:

$$ident \texttt{ = fun } pattern_1 \ ... \ pattern_n \texttt{ => } expr$$

can be declared in the following way:

$$\texttt{node } ident \ pattern_1 \ ... \ pattern_n \texttt{ = } expr$$

Both forms define *ident* to be a function with n arguments.

Shared Memory Initialization

A definition `last` *ident* `=` *expr* defines a shared memory `last` *ident* to be initialized with the value of *expr*.

Signal Definition

A definition `emit` *ident* `=` *expr* defines the signal *ident* to be equal to the value of *expr*.

Pattern Matching

`match` *expr* $pattern_1$ `->` $action_1$ `|` ... `|` $pattern_n$ `->` $action_n$ `end` is used for combining n complementary sub-streams. Each of these streams is on the clock defined by the instants where the value of e has the form $pattern_i$.

Each *action* is made of a (possibly empty) sequence of local definitions and a definition list of shared variables. These shared variables can appear in several branches.

Modular Reset

The construction `reset` $definition_1$ `and` ... `and` $definition_n$ `every` *expr* allows for resetting the computation made in a set of definitions. All the defined values and expression *expr* must be on the same clock. This construction acts as a regular multi-definition except that all the streams and automata defined in $definition_1$,..., $definition_n$ restart with their initial value every time the current value of *expr* is true. In particular automata restart into their initial state.

Automata

The construction `automaton` *def-automaton-handler* `|` ... `|` *def-automaton-handler* `end` defines an automaton. Each branch of the automaton is of the form:

constructor `->` *automaton-action*

or

constructor pattern `->` *automaton-action*

where *constructor* denotes the name of the state. This state may be parameterized by a pattern. The first branch defines the initial state and this state cannot be parameterized.

The action associated to a state is of the form:

local-definitions `do` *definition-list transitions*

It is made of a (possibly empty) sequence of local definitions to the state, a definition list of shared variables and a (possibly empty) list of transitions which are tested sequentially. Transitions may have several forms. Writting:

`until` *signal-pattern* `then` *state-expression*

defines a *weak transition* which is executed at the end of the reaction, that is, *after* definitions from the current state have been executed. When the conditions succeed, the new state is given by the value of *state-expression*. The keyword `then` indicates that the new state is *entered by reset*, that is, all the streams and automata in the next state restart with their initial value. Writting:

`until` *signal-pattern* `continue` *state-expression*

has the same behavior except that the next state is *entered by history*, that is, no reset occurs.

The language provides two derived forms of transitions written `then` *state-expression* and `continue` *state-expression* as short-cut of `until true then` *state-expression* and `until true continue` *state-expression*.

Moreover, transitions may be either weak of strong. The following form:

`unless` *signal-pattern* `then` *state-expression*

defines a *strong transition* which is executed *before* the reaction starts, that is, before definitions from the current state have been executed. When the conditions succeed, the definitions to be executed belong to the value of *state-expression*. The keyword `then` indicates that the new state is entered by reset, that is, every stream and state from the value of *state-expression* are reseted. Finally, writting:

`unless` *signal-pattern* `then` *state-expression*

defines a strong transition with entrance by history.

Testing the Presence of Signals

A present statement is pretty much the same as a pattern-matching statement. It is of the form:

`present` *def-present-handler*$_1$ `|` ... `|` *def-present-handler*$_n$ `end`

Where a handler is of the form:

signal-pattern `->` *action*

Signal patterns are tested sequentially and the one which succeed defines the corresponding action to execute. Finally, a handler:

`_ ->` *action*

defines a condition which always succeed.

3.11 Type definition

Abstract types can be defined. Their syntax is inherited from Objective Caml and is reminded here.

type-definition ::= `type` *typedef* { `and` *typedef* }

typedef ::= [*type-params*] *typeconstr-name*
| *sum-type-def*
| *record-type-def*

sum-type-def ::= [`|`] *one-sum-def* { `|` *one-sum-def* }

one-sum-def ::= *capitalized-ident*
| *capitalized-ident* `of` *type*

record-type-def ::= { *label-type* { `;` *label-type* } }

label-type ::= *ident* `:` *type*

type-params ::= `'` *ident*
| `(` `'` *ident* { `,` `'` *ident* } `)`

3.12 Module implementation

implementation ::= { *impl-phrase* [`;;`] }

impl-phrase ::= *value-definition*
| *type-definition*
| `open` *module-name*

value-definition ::= `let` [`rec`] *let-binding* { `and` *let-binding* } [`;`]

A module implementation consists in a sequence of implementation phrases. An implementation phrase either opens a module, is a type definition or is a sequence of definitions.

- The instruction `open` modifies the list of opened modules by adding the module name to the list of opened modules, in first position.
- The type definition defines the type for the implementation phrases following the definition.
- The value definition defines some global values.

3.13 Scalar Interfaces and Importing values

Scalar interfaces written in Objective Caml can be imported by Lucid Synchrone. In the current implementation, a restricted subset of Objective Caml interfaces is considered. The syntax is the following:

scalar-interface	:: =	{ *scalar-interface-phrase* [`;;`] }
scalar-interface-phrase	::=	*value-declaration*
	|	*type-definition*
value-declaration	::=	`val` *ident* `:` *type*

When a value is imported from the host language Objective Caml the value is automatically lifted to the stream level in the following way.

- A scalar value with a basic or declared type becomes a infinite stream of that type.
- A scalar functional value becomes a stream functional value applied point-wisely to its argument.

3.13.1 Making a Node from an Imported Value

It is possible to build a node from a pair $(s_0, step)$ of type $a \times (a \rightarrow b \rightarrow c \times a)$. s_0 stands for the initial state and *step* for the step function. The step function takes the current state, an input (with type b) and returns a value (with type c) and a new state. Such a pair can be transformed into a node by defining a lifting function like the following (other encoding are of course possible).

```
let node instance (s0, step) input =
  let rec last s = s0
  and o, s = step (last s) input in
    o

val instance :  'a * ('a -> 'b -> 'c * 'a) -> 'b => 'c
val instance :: 'a * ('a -> 'b -> 'c * 'a) -> 'b -> 'c
```

Chapter 4

`lucyc` - The batch compiler

This part describes how to transform Lucid Synchrone programs into Objective Caml programs. This is achieved by the command `lucyc`.

```
lucyc [-stdlib lib-dir] [-civ] [-realtime] [-s node]
      [-I lib-dir] [-print] [-inline level] [-sampling n] filename ...
```

`lucyc` accepts four kinds of arguments:

- Arguments ending in `.ls` are considered to be Lucid Synchrone source files. A file `.ls` is a sequence of node declarations. From a file `f.ls`, the `lucyc` compiler produces a compiled interface `f.lci` and an Objective Caml file `f.ml` containing the implementation. The `.ml` file defines the corresponding transition functions for the values defined in the input file.
- Argument ending in `.lsi` are considered to be Lucid Synchrone interfaces, defining types and clocks for every value defined in the implementation. From a file `f.lsi`, the compiler produces a compiled interface `f.lci`.
- Argument ending in `.dcc` are considered to be declarative files. They are pre-compiled intermediate files obtained using option `c`.
- Arguments ending in `.mli` are considered to be Objective Caml interface files. From a file `f.mli`, the `lucyc` compiler produces a compiled interface `f.lci`. Every value defined in `f.mli` is considered to be a scalar value.

The following options are accepted by the `lucyc` command:

`-stdlib lib-dir` Directory for the standard library.

`-c` Compile only. Produces a file ending in `.dcc` containing an intermediate representation of the source program and a file ending in `.lci` containing a compiled interface.

`-i` Print types and clocks. The output can be used directly for building Lucid Synchrone interfaces.

`-v` Prints the compiler version number.

`-realtime` Real-time mode of the compiler. Only accept programs for which the generated transition function can be executed in bounded time and memory. In the current implementation, only non recursive nodes are allowed.

`-s node` Produces a file `node.ml`, containing the transition function for the value `node`.

`-I lib-dir` Adds `lib-dir` to the path of directories searched for compiled interface files `.lci`.

`-inline level` Sets the level of inlining to `level`. The value should be a integer. The greater the value is, the greater is the inlining (beware that the code size may increase)

`-print info` Print information according to `info`:

`type` print type

`clock` print clock type

`caus` print causality type

`init` print initialization type

`all` print all types

`-sampling n` Set the sampling frequency to 1/n. When [n=0], the program is executed at full speed.

Warning: It is essential that the sampling rate given here be the same as the one used in the synchronous program. Moreover, the user must check that the execution time of the reaction is always less than the sampling rate.

SEE ALSO

distribution and manual at `www.lri.fr/~pouzet/lucid-synchrone`.

FILES

`/usr/local/bin/lucyc`	the compiler
`/usr/local/lib/lucid-synchrone`	the standard library

Chapter 5

The simulator

Appart from the compiler, a simple simulator is proposed for observing a program. It is connected to the chronogram Sim2chro if it is available.

```
lucys -s node [-v] [-tk] filename.lci
```

`lucys` is a simulator for the Lucid Synchrone programming language (see `lucyc`). `lucys` generates an Objective Caml program for simulating a node `node` defined in the compiled interface `filename.lci`. This program produces a graphical interface allowing the user to give some inputs to the node and to compute the current reaction.

In order to simulate a node `node` from a source file `filename.ls`, you must type:

```
lucyc -s node filename.ls
lucys -s node filename.lci
```

Once the simulator have been generated, it should in turn be compiled with the Objective Caml compiler by typing the following command:

```
ocamlc -o node unix.cma -I +lablgtk2 lablgtk.cma <obj_files> <node>_sim.ml
```

The graphic window of the simulator is organised as follows: the inputs are given on the top left; the outputs on the top right and control buttons are given on the bottom. Each input and each output is represented by one button. The presentation of the buttons follows the tree structure of the node's type.

Two modes are provided for simulating the node. In the "step" mode, the user sets several inputs and the reaction is computed when pressing the button "step". When the "step" button is switched on "autostep", an output is computed as soon as a boolean input becomes true. The "reset" button is used to reset the node, which gets back to its initial state.

When the tool `sim2chro` has been installed, input/output of the node are given to him for printing a chronogram. Otherwise, the simulator only provide a limited chronogram facility.

The following options are accepted by the lucyc command:

`-s node` Produces an event driven simulator `node_sim.ml` for `node`. The node should be defined in the compiled interface `filename`. Moreover, some type and clock restrictions apply to the node (see Restrions below).

Once the simulator have been generated, it should in turn be compiled with the Objective Caml compiler by typing the following command:

```
ocamlc -o node -I +lablgtk2 lablgtk.cma <obj_files> <node>_sim.ml
```

5.1 Restrictions

In the current implementation the following restrictions apply :

Types Only the primitives types can be simulated (`bool`, `int`, `float`, `string`, `unit`) and any product of those.

Clocks The node must not contain sampled clocks (no `on` operator should appear in the clock).

5.2 Availability

The event-driven interfaces generated use the LablGTK2 library. The installation of this library is also required to compile these interfaces.

LablGTK2:
http://wwwfun.kurims.kyoto-u.ac.jp/soft/lsl/lablgtk.html

The tool `sim2chro` can be called directly from the simulator provided it is reachable from the `PATH` variable. For installing it, see:

Linux:
http://www-verimag.imag.fr/~remond/SIM2CHRO/index.html

MacOSX (universal):
http://www-verimag.imag.fr/~raymond/edu/distrib/index.html
http://www-verimag.imag.fr/~raymond/edu/distrib/macosx/README-SIM2CHRO

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